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Model-based subtraction of spikes from surface nuclear magnetic resonance data

Jakob Juul Larsen¹

ABSTRACT

Surface nuclear magnetic resonance (surface NMR) has progressed significantly in recent years due to advances in instrumentation. In particular, the introduction of multichannel surface NMR instruments has been effective in improving the signal-to-noise ratio. The current methodology for noise reduction with multichannel instruments is, however, inadequate in complex noise environments, and there is a need for improved signal processing. We have evaluated a study of impulsive noise (spikes) in surface NMR data acquired with a Numis Poly instrument. We have determined how the spectral content can be used to classify spikes as originating from electric fences or sferics. Measurements of spikes from two electric fences were evaluated. The spikes were highly deterministic and can be modeled as impulsive excitations of the band-pass filter in the surface NMR receiver system. We investigated the feasibility of a model-based approach for subtraction of electric fence spikes. Model-based subtraction was shown to be possible, but it is limited by accidental fitting of the NMR signal in its current embodiment. We evaluated an example of a surface NMR data set in which subtraction of powerline harmonic noise and electric fence spike noise removed all coherence in the multichannel data, and the consequences for further noise reduction using multichannel methods were developed.

INTRODUCTION

Groundwater is the key resource for water supply and irrigation in many parts of the world, but it is often a scarce resource. The demand for groundwater is steadily increasing, and there is a need for reliable tools that can aid in sustainable management of groundwater.

Surface nuclear magnetic resonance (surface NMR) has been recognized as one such tool (Legchenko and Valla, 2002; Hertrich, 2008; Yaramanci and Müller Petke, 2009; Behroozmand et al., 2015). The technique is based on the standard principles of NMR. Subsurface hydrogen nuclei in liquid water residing in the static magnetic field of the earth are excited by an electromagnetic pulse transmitted from a surface-based coil. During the subsequent relaxation of the hydrogen nuclei, a secondary electromagnetic field is emitted. This signal is recorded on the surface either with the coil used for excitation or a designated receiver coil. The recorded signal is a transient voltage oscillating at the Larmor frequency. The initial amplitude is directly proportional to the number of excited hydrogen nuclei, i.e., the groundwater content. Further, the relaxation of the NMR signal can be used to estimate the pore size distribution and the hydraulic parameters in the subsurface. When the amplitude of the excitation pulse is increased, deeper lying hydrogen nuclei are effectively excited and through a subsequent inversion of the gathered NMR signals, depth resolved estimates of the groundwater content and the hydraulic parameters down to approximately 100 m can be obtained (Mohnke and Yaramanci, 2008; Behroozmand et al., 2015). Surface NMR is unique among the geophysical techniques because it is the only noninvasive method that is directly sensitive to water in the subsurface.

The overwhelming challenge of using surface NMR for exploring and quantifying groundwater systems is the signal-to-noise ratio (S/N), which is often very poor (Legchenko, 2007; Chalikhakis et al., 2008). The signal level is governed by the actual amount of water in the subsurface and the signal level cannot, as such, be increased. When larger coils are used, an NMR signal is captured from a larger volume giving a larger recorded signal, but more noise is also captured, and effectively, the S/N is not improved. Recently published work has shown that increased signal levels can be obtained through an improved excitation of the hydrogen nuclei using adiabatic pulses, but the method is still in the early research stage (Grünwald et al., 2015). At this stage, the path toward increased S/N is thus through decreasing the noise level by improved signal processing.

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The focus of this paper is the removal of one particular noise component, i.e., impulsive noise (spikes) from electric fences through a subtraction-based approach. In principle, electric fence spikes can be avoided by having nearby fences turned off during measurements, but when this is not possible, other methods are needed. Large spikes are easily identified in surface NMR data and removed by, e.g., zeroing the affected data, but valuable NMR signal is lost in this process and discontinuities are introduced in the data with negative effects for subsequent noise reduction using multichannel filtering. The hypothesis investigated in this paper is that spikes from electric fences are highly deterministic and can be modeled as impulsive excitations of the surface NMR receiver system.

The outline of the paper is as follows: In the next section, a brief overview of noise affecting surface NMR data is given. This is followed by an investigation of spikes using a high bandwidth receiver system. The data are used to devise two simple spike models and their applicability is tested. The paper proceeds with an analysis of the coherence of multichannel surface NMR data when harmonic noise and spikes are subtracted. Conclusions and directions for further work are given in the final section.

NOISE IN SURFACE NMR DATA

Analysis of noise in surface NMR measurements have been reported by many authors, and the consensus is that surface NMR measurements are primarily affected by two noise sources (Plata and Rubio, 2002; Legchenko and Valla, 2003; Costabel and Müller Petke, 2014; Dalgaard et al., 2014; Larsen et al., 2013; Müller Petke and Costabel, 2014). The first major noise source is harmonics from powerlines; i.e., sinusoidal signals with frequency mf_0 , where f_0 is the fundamental powerline frequency and m is an integer. The second major noise source is spikes, i.e., short impulsive noise events. The most often encountered sources of spikes are electric fences and thunderstorms.

The signal sampled from a surface NMR receiver coil at time nT_s , where n is an integer and T_s is the sampling period, is denoted by $p(n)$. This signal can be decomposed into four parts

Figure 1. Example of a surface NMR recording in a complex noise environment. Two spikes labeled A and B are recorded in four channels. The ratio of amplitudes of the two spikes is different in all channels.

$$p(n) = \text{NMR}(n) + h(n) + sp(n) + w(n), \quad (1)$$

where $\text{NMR}(n)$ denotes the NMR signal, $h(n)$ is the powerline harmonic noise, and $sp(n)$ represents spikes and any remaining noise components from unidentified sources, receiver electronics, etc. are collected in $w(n)$. The noise cannot be efficiently suppressed by simple band-pass and notch filters because the spectra of the NMR signal and the noise overlaps.

Multichannel filtering

New multichannel surface NMR instruments improve noise reduction by using one or several additional reference receiver coils placed distant from the primary NMR receiving coil to record only noise. When the reference coil noise is correlated with the noise in the primary coil, it can be filtered and subtracted from the primary coil data and a noise-reduced NMR signal results (Radic, 2006; Walsh, 2008; Dlugosch et al., 2011; Dalgaard et al., 2012).

The multichannel filtering technique works well in many cases, but it fails in complex, multisource noise environments, such as the one shown in Figure 1. The data presented in the figure are recorded with a four-channel (one primary coil and three reference coils) Numis Poly from Iris Instruments, France. Two different spikes, labeled A and B, are observed 30 and 45 ms into the time series. The amplitude ratios between the A and the B spikes are very different in the four channels. In the primary coil, the amplitude ratio is approximately 2, whereas the amplitude ratio is close to unity in reference coil 3. In reference coil 1, the amplitude ratio is ill-defined because the B spike is hardly visible. The implication of this observation is that the optimum filter for subtraction of the A spike in the primary coil using, e.g., reference coil 3 is different from the optimum filter for subtraction of the B spike in the same coils. With current signal processing methodologies, the designed filter will be a compromise between the two optimum filters and neither spike will be adequately removed.

A block diagram showing this explicitly for a two-channel instrument is given in Figure 2. Two different noise sources are observed in a primary coil and a reference coil. The different paths, e.g., distance, from the two noise sources into the two coils are modeled by in the z -domain by four transfer functions $H_{N_1P}(z)$, $H_{N_1R}(z)$, $H_{N_2P}(z)$, and $H_{N_2R}(z)$ (Hayes, 1996). The indices on the transfer

Figure 2. Block diagram of a two-channel surface NMR instrument and two noise sources. The different paths from the two noise sources into the primary and reference coils are modeled by four transfer functions.

functions label the noise source and receiver coil, and $S(z)$ represents the optimum transfer function for noise cancellation. For noise source 1, $S(z)$ is given by

$$S(z) = \frac{H_{N_1P}(z)}{H_{N_1R}(z)}, \quad (2)$$

whereas it takes the form

$$S(z) = \frac{H_{N_2P}(z)}{H_{N_2R}(z)} \quad (3)$$

for noise source 2, which is different from the first expression for $S(z)$. Advanced signal processing algorithms, explicitly designed to cope with complex noise environments are thus needed before full advantage can be taken of the multichannel surface NMR instruments.

Modeling of powerline harmonics

One step in dealing with complex noise environments was recently taken by the author and coworkers (Larsen et al., 2013). Building upon previous work on removing powerline harmonic interference in geophysical measurements (e.g., Butler and Russell, 1993; Legchenko and Valla, 2003), it was shown that a model of the powerline harmonic interference can be fitted to the signal acquired in each coil and subsequently subtracted. The harmonic noise model is given by

$$h(n) = \sum_m A_m \cos(2\pi m f_0 n T_s + \phi_m), \quad (4)$$

where A_m and ϕ_m are the amplitude and phase of the m th harmonic, respectively. The model uses that all harmonics are intrinsically locked to the fundamental powerline frequency. The effect of the subtraction is that one of the two major noise sources is eliminated. The complexity of the remaining noise is, however, not entirely eliminated, as is evident from the above discussion of spikes and shown in Figure 1. Further, small spikes that were masked by the powerline harmonic interference are often evident in the data after subtraction of the powerline noise model (Larsen et al., 2013).

Impulsive noise

Impulsive noise has been studied intensively in, e.g., biomedical signal processing, but only a limited number of papers dealing with this type of noise in surface NMR have been published. The general philosophy behind impulsive noise detection is to declare an impulsive noise event when the signal exceeds some chosen threshold. The choice of threshold is a balance between capturing all spikes, while avoiding false detections. Plata and Rubio (2002) make surface NMR measurements in the south of Spain and apply “surgical muting,” i.e., spikes with an amplitude greater than a selected threshold are rejected. The rejection is done for each measurement before stacking, but as the authors point out, spikes below the threshold are not rejected and add noise to the final result. A similar rejection approach has been used by other groups (e.g., Legchenko, 2007). Statistical stacking procedures to reject spikes have also been investigated (Jiang et al., 2011). The authors found that statistical stacking of their data could improve S/N by a factor of 4–7 in areas with many spikes.

Dalgaard et al. (2012) also apply a threshold detection method to identify spikes. To increase the detection sensitivity, a nonlinear

energy operator was applied to preemphasize the spikes before applying a threshold defined by the median absolute deviation of the data series. They are concerned with noise reduction in a multichannel surface NMR system and use the spike identification to reject segments of data containing spikes in the calculation of transfer functions, multichannel filtering, and stacking.

An investigation of noise affecting surface NMR data is carried out by Dalgaard et al. (2014). Using a two-coil data acquisition device and decomposition of the recorded signals into noise categories, comprehensive noise maps are presented showing the spatial variation of powerline harmonic noise, spike noise, and random noise. The amplitude dependence with distance of spikes from an electric fence is also investigated. In the near-field of the fence, a constant value is observed and in the far-field, the amplitude decays as $1/r^2$.

An interesting approach toward removal of impulsive noise is published by Costabel and Müller Petke (2014). The authors investigate the use of wavelet decomposition of the acquired signals and compare that with the standard thresholding approaches. In wavelet decomposition, successive high- and low-pass filters give a time-frequency resolution of the signal, and impulsive noise shows up as enlarged wavelet coefficients. Impulsive noise is cancelled by setting the wavelet coefficients above a specified threshold to zero before reconstructing the signal. A significant sensitivity to the choice of wavelet base is reported, and importantly, overfitting of the data resulting in underestimation of the NMR amplitude is also observed. Costabel and Müller Petke (2014) conclude that standard threshold methods currently outperform wavelet decomposition, but wavelet-based denoising strategies have interesting properties for further work.

It is difficult to directly compare the above-mentioned approaches for two reasons: First, the data used in the analysis of noise have been recorded on different surface NMR instruments. The bandwidth of the instrument and any filters applied to the signals will significantly change the shape of the impulsive noise. Second, impulsive noise can originate from vastly different sources and the analysis of the noise changes accordingly. For example, the observation of series of spikes within short time intervals of tens of milliseconds are reported (Costabel and Müller Petke, 2014).

IMPULSIVE NOISE IN SURFACE NMR SIGNALS

Field examples

Spikes originate from many different sources, electrical fences, thunderstorms, airports, etc. and the exact appearance of the spikes can change accordingly. Two examples of spikes and their spectra are given in Figures 3 and 4. The presented data were recorded near Odder, Denmark, with a Numis Poly system from Iris Instruments. The Numis Poly receiver system is equipped with a hardware-based fourth-order band-pass filter with a bandwidth of 150 Hz and tunable center frequency that is fixed at 2150 Hz for these measurements. The sampling frequency of the system is 19.2 kHz. Powerline harmonics have been subtracted from the measurements before plotting. A typical example of a spike from a nearby electric fence is plotted in Figure 3. In the time domain, a smooth envelope with a carrier wave at approximately 2150 Hz is observed. The duration of the spike is slightly less than 10 ms. The spectrum of the spike is plotted in the bottom part of Figure 3. A broad featureless peak with a center at the band-pass filter is observed. Both of these

observations can be attributed to an impulsive excitation of the fourth-order band-pass filter in the instrument.

A very different example of a spike is plotted in Figure 4. The spike is amplitude-asymmetric and has a short duration of approximately 0.5 ms. The spectrum of this spike is dominated by a broad high-frequency peak extending from 4 up to 9.6 kHz and bears no resemblance to the spectral shape of the band-pass filter. This spike can be ascribed to an audio frequency sferic from a remote thunderstorm (Hennessy and Macnae, 2015). The spectrum of audio frequency sferics typically extends from a few kHz to several tens of kHz. The combination of the audio frequency sferic, the band-pass filter, and aliasing give rise to the peculiar shape of the observed spectrum.

Figure 3. Example of a spike from an electric fence. The power spectral density is shown in the inset.

Figure 4. Example of a sferic. The power spectral density is shown in the inset. The peculiar shape of the spectrum is caused by the majority of the energy in the sferic being located at high frequencies exceeding the center frequency of the band-pass filter and half of the sampling frequency.

In a surface NMR measurement, both types of spikes are often observed. Sferics typically have a large variability, and the presence of a sferic is very much dependent on the geographical position, season, and time of day. The variability of spikes from electric fences is much smaller due to their man-made origin, and this can potentially be used to remove electric fence spikes from surface NMR measurements.

High bandwidth spike measurements

To validate the hypothesis that spikes from electric fences being due to (near) impulsive excitations of the surface NMR instrument with a subsequent temporal shape governed by the instrument band-pass filter, several spike measurements were undertaken with a noise recording instrument (Dalgaard et al., 2014). Briefly, the instrument consists of two seven-turn, 10×10 m coils with amplifiers attached. Signals are measured by a 16 bit, USB controlled digital oscilloscope with a maximum sampling rate of 5 MHz. The bandwidth of the system, coils, and amplifiers exceeds 100 kHz.

An example of a spike from an electric fence is given in Figure 5. The data were recorded with 5 MHz sampling rate, and no additional low-pass filters were applied to the data. The spike is described by a main peak followed an oscillating tail. The power spectral density of the spike is plotted in the inset. The bandwidth of the spike is approximately 50 kHz and well within the detection range of the instrument. The duration of the entire spike is approximately 800 μ s, but analysis of the spike shows that 90% of the energy is located within the first 50 μ s. For the Numis Poly system, the 19.2 kHz sampling rate equals a sampling period of 52 μ s, thus the excitation of the surface NMR instrument by a spike from an electric fence can be considered as an almost impulsive excitation. If a digital band-pass filter with center frequency and bandwidth similar to the Numis Poly hardware filter is applied to the recorded spike, the result is a spike with a shape completely similar to the spike plotted in Figure 3.

Overlaying plots (eye diagrams) of 17 and 15 spikes from two different electric fences are plotted in Figure 6. Spikes from both

Figure 5. Electric fence spike recorded with a high-bandwidth system. The duration of the entire spike is less than 0.8 ms, and 90% of the spike energy is contained in the first 50 μ s. The inset shows the power spectral density of the spike.

fences correspond to nearly impulsive events, but the detailed shape is slightly different. All the spikes recorded from fence A are almost identical with a less than $\pm 0.25\%$ variation in energy. The variation of the energy in spikes from fence B is $\pm 15\%$. This is caused by the spikes from fence B falling into two distinct classes with either high or low energy. Within each class, the variation is less than $\pm 1\%$.

The above observations are important because it can be concluded from them that spikes originating from electric fences correspond to nearly impulsive excitations of the surface NMR instrument and subsequent spikes will be very nearly identical. This suggests that the subtraction of spikes from electric fences is a feasible approach for noise reduction.

Locating spikes in the time domain

The standard methods of locating spikes are based on comparing the local signal level with a specified threshold. This approach cannot distinguish between spikes from electric fences and sferics without further processing. The spectral content of the two types of spikes is markedly different (Figures 3 and 4). Simple preprocessing consisting of a low-pass or band-pass filtering of the signals preferentially removes sferics and subsequent thresholding captures only spikes from electric fences or similar sources. Likewise, sferics can be enhanced, if needed, by band-stop or high-pass filtering.

Before thresholding, the nonlinear energy operator,

$$\psi[x(n)] = x^2(n) - x(n-1)x(n+1), \quad (5)$$

where $x(n)$ is the data sampled at time nT_s and used to preemphasize the spikes.

Optimization of the threshold operation is achieved by applying a generalized nonlinear operator (Lin et al., 1995):

$$\psi_k[x(n)] = x^2(n) - x(n-k)x(n+k), \quad (6)$$

with $k = 2, 3, \dots$ gives a larger nonlinear signal but does not increase the detection efficiency as the background signal is similarly increased. Further details on preemphasizing spikes before thresholding can be found in Dalgaard et al. (2012). Spikes from electric fences are normally very stable in amplitude from spike to spike and also in the spike to spike distance. With surface NMR systems providing time-stamped data, this can be used to aid the detection and classification of spikes.

Spike modeling

The impulsive excitation of the surface NMR instrument by an electric fence is modeled in the continuous time domain as an impulse with amplitude A at time t_0 , $A\delta(t - t_0)$ convolved with the impulse response of the receiver system $g_{\text{rec}}(t)$. The resulting spike, before sampling, is denoted by $sp(t)$:

$$sp(t) = A\delta(t - t_0) * g_{\text{rec}}(t). \quad (7)$$

The Numis Poly receiver system is modeled as a tunable fourth-order band-pass filter. As the exact details of the tunable receiver electronics are unavailable, we propose to model the fourth-order band-pass filter as cascades of either two identical or two different second-order band-pass filters. The transfer function of a second-

order band-pass filter in the s domain is given by (Thomas and Rosa, 2004)

$$G(s) = \frac{s}{s^2 + 2\zeta\omega_0 s + \omega_0^2}, \quad (8)$$

where ω_0 and ζ are the center frequency and bandwidth of the filter and s is the complex frequency. Any gain in the filters are tacitly included in the spike amplitude A . The impulse responses are derived in Appendix A and give the spike model when multiplied by the amplitude and time shifted to t_0 . A Heaviside step function forces the model expression to zero for $t < t_0$.

For each 1 s signal record, an initial identification of spikes is done using the spike location algorithm described above. Subsequently, the powerline harmonic model is fitted on data without spikes. The model is extrapolated to the 1 s record and subtracted before spike modeling (Larsen et al., 2013). The approximate locations of spikes are known from the spike location algorithm and used to cut out 20 ms segments containing single spikes. The spike in each segment is independently least-squares fit to the model with A , t_0 , and the filters center frequency and bandwidth as fitting parameters. The fitting uses initial estimates of the amplitude and time shift obtained from the location of the largest sample in the segment. Initial estimates for the center frequency and bandwidth are based on the approximate values known for the Numis Poly system.

The performance of the spike model assuming cascaded identical second-order filters is illustrated in Figure 7. The model has been fit to a data set without a surface NMR signal and powerline harmonics. At first sight, the model appears adequate (Figure 7a), but inspection of the time series after the model has been subtracted (Figure 7b) reveals that a significant spike remains in the data. When the degrees of freedom in the spike model are increased from four to six by assuming cascaded different second-order filters with independent center frequencies and bandwidths, the performance is significantly improved as evident in Figure 8. A small artifact remains close to t_0 . The likely explanation of the artifact is that the excitation is only near-impulsive (Figure 6).

Figure 6. Eye diagrams of spikes from two electrical fences: 17 spikes from fence A and 15 spikes from fence B are plotted.

Subtraction of spikes in the presence of an NMR signal

Accidental modeling of the NMR signal in model-based powerline harmonic subtraction algorithms can lead to wrong estimates of the water content and relaxation times (Larsen et al., 2013). The same problem also occurs when spikes are modeled and subtracted.

An example of this is presented in Figure 9. In Figure 9a, a simplistic, synthetic NMR signal given by

$$\text{NMR}(n) = N_0 \cos(2\pi f_L n T_s + \phi) e^{-n T_s / T_2^*}, \quad (9)$$

with $N_0 = 500$ nV, $T_2^* = 100$ ms, and $f_L = 2137$ Hz is added to a surface NMR noise-only record, where powerline harmonics had been removed. The record contains an electric fence spike 40 ms

Figure 7. Modeling of a spike from an electric fence with a receiver system modeled as a cascade of two identical second-order band-pass filters. (a) Full curve shows recorded data and diamonds show the fitted model. (b) The residual signal after subtraction of the spike.

Figure 8. Model of a spike from an electric fence with a receiver system modeled as a cascade of two different second-order band-pass filters. (a) Full curve shows recorded data and diamonds show the fitted model. (b) The residual signal after subtraction of the spike.

into the time series. The spike is modeled as an impulsive excitation of a cascade of two different band-pass filters and subtracted from the data. A significant distortion of the NMR signal is observed (Figure 9b). The distortion occurs when the NMR signal is wrongly modeled as spike signal and subtracted.

The cause of the overfitting is the similarity between the NMR signal and the signal from the electric fence spike. The NMR signal oscillates at the Larmor frequency and the spike oscillates at a frequency close to the center frequency of the band-pass filter, which is tuned close to the Larmor frequency. Overfitting can also be observed on some spikes in noise-only records. This is caused by the oscillatory character of the background noise after passing through the band-pass filter.

COHERENCE AFTER NOISE SUBTRACTION

When powerline harmonics and electric fence spikes are subtracted from surface NMR records, a significantly reduced complexity of the noise environment is achieved. An important question to answer is then how much coherence remains between signal recorded in the primary coil and signals recorded in reference coils. If the coherence is low; i.e., the signals are uncorrelated, additional multichannel filtering cannot improve the S/N.

An analysis of the coherence in a noise-only data set as noise components are selectively subtracted is provided in Figure 10. The raw signals from the primary coil and a reference coil are plotted in the top row along with the coherence between the two signals. The coherence is seen to be high at many of the powerline harmonic frequencies and lower in-between. Parts of the lower coherence in-between the harmonic frequencies are caused by interference between spikes originating from multiple sources. High-coherence values very close to one are obtained when the coherence is calculated from short segments containing a single spike.

The signals obtained by subtracting powerline harmonics are plotted in the middle row. Small spikes that were initially masked by the powerline harmonic noise are now evident in the data. The coherence at the powerline harmonic frequencies has disappeared

Figure 9. Subtraction of a spike in the presence of a synthetic NMR signal. (a) Synthetic NMR signal embedded in a noise-only record with an electric fence spike. (b) The signal after subtraction of the spike. The spike is overmodeled and the NMR signal is subtracted.

Figure 10. Coherence between the primary coil and reference coil signals. (Top) Raw signals and coherence; (middle) signal and coherence after subtraction of powerline harmonics; and (bottom) signal and coherence after subtraction of powerline harmonics and spikes.

and only a broad, low coherence, peak at the center of the band-pass filter is observed. Again, if the coherence is calculated from short segments of data containing a single spike, coherence values very close to one are obtained.

The signals obtained by also subtracting electric fence spikes are plotted in the bottom row. No significant coherence is observed in this case. This surprising absence of coherence implies that the coherence in the raw signals is solely due to powerline harmonics and electric fence spikes. The residual noise is incoherent between the channels and can only be reduced through filtering or averaging. It must be emphasized that the data set analyzed above is recorded in Denmark and is practically devoid of sferics. When the same analysis is done on data sets containing sferic components, some coherence remains due to the sferics. Analysis of data obtained in other parts of the world where remote thunderstorms are important sources of noise will give less clear results.

CONCLUSIONS

The feasibility of improving the S/N in surface NMR data by subtraction of spikes has been investigated. It was shown that spikes from electric fences correspond to near-impulsive excitations of the Numis Poly receiver system, which can be efficiently modeled as a cascade of two band-pass filters. In its current form, the approach suffers from overfitting and subtraction of the NMR signal. Further work on resolving this issue is needed before the approach is viable for field use. Potential solutions include constrained fitting procedures where prior knowledge of the band-pass filter, obtained through statistics based on many spike records, or through accurate measurements of the receiver electronics are used to reduce the degrees of freedom in the model, or advanced multichannel methods where spikes observed in several coils are fitted simultaneously.

Spikes from sferics are much more random and cannot be reduced by the proposed approach. The sferics typically observed in Denmark are rare and short events with a duration less than 1 ms. Such sferics are adequately rejected with threshold methods. Sferics observed at other locations are more ubiquitous and can persist for

many milliseconds. For rejection of this type of spikes, multichannel filtering is needed or hardware with improved immunity to noise.

The coherence between the signal from a primary coil and a reference coil was analyzed as powerline harmonics and electric fence spikes were subsequently subtracted. No coherence was observed after the subtraction. This result can therefore be interpreted as the site and instrument specific lower noise limit obtainable without averaging of signal records.

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APPENDIX A

IMPULSE RESPONSE OF FOURTH-ORDER BAND-PASS FILTERS

The transfer function of a fourth-order band-pass filter modeled as a cascade of two identical second-order band-pass filters each with a transfer function given by equation 8 is

$$G_{4,I}(s) = \left(\frac{s}{s^2 + 2\zeta\omega_0 s + \omega_0^2} \right)^2. \quad (\text{A-1})$$

The corresponding impulse response is found by an inverse Laplace transform:

$$g_{4,I}(t) = \frac{1}{2} e^{-\zeta\omega_0 t} \left(\frac{(\zeta^2 - 1)^{-\frac{3}{2}} (-2\zeta^3\omega_0 t + 2\zeta\omega_0 t - 1) \sinh(\omega_0 \sqrt{\zeta^2 - 1} t)}{\omega_0} + \frac{t(2\zeta^2 - 1) \cosh(\omega_0 \sqrt{\zeta^2 - 1} t)}{\zeta^2 - 1} \right). \quad (\text{A-2})$$

For filters that are nonidentical, second-order sections are given by

$$G_a(s) = \frac{s}{s^2 + 2\zeta_a\omega_a s + \omega_a^2} \quad (\text{A-3})$$

and

$$G_b(s) = \frac{s}{s^2 + 2\zeta_b\omega_b s + \omega_b^2}; \quad (\text{A-4})$$

the transfer function is $G_{4,II}(s) = G_a(s)G_b(s)$ and the impulse response is given by

$$\begin{aligned}
g_{4,II}(t) = & \frac{1}{4\zeta_a^2\omega_a^2\omega_b^2 - 4\zeta_a\zeta_b\omega_a^3\omega_b - 4\zeta_a\zeta_b\omega_a\omega_b^3 + 4\zeta_b^2\omega_a^2\omega_b^2 + \omega_a^4 - 2\omega_a^2\omega_b^2 + \omega_b^4} \\
& \times \left(\frac{\omega_a(2\zeta_a^2\omega_b^2 - 2\zeta_a\zeta_b\omega_a\omega_b + \omega_a^2 - \omega_b^2) \sinh\left(\omega_a\sqrt{\zeta_a^2 - 1}t\right) e^{-\zeta_a\omega_a t}}{\sqrt{\zeta_a^2 - 1}} \right. \\
& + \frac{\omega_b(2\zeta_b^2\omega_a^2 - 2\zeta_a\zeta_b\omega_a\omega_b - \omega_a^2 + \omega_b^2) \sinh\left(\omega_b\sqrt{\zeta_b^2 - 1}t\right) e^{-\zeta_b\omega_b t}}{\sqrt{\zeta_b^2 - 1}} \\
& + 2(\zeta_a\omega_b - \zeta_b\omega_a)\omega_a\omega_b \left(\cosh\left(\omega_b\sqrt{\zeta_b^2 - 1}t\right) e^{-\zeta_b\omega_b t} \right. \\
& \left. \left. - \cosh\left(\omega_a\sqrt{\zeta_a^2 - 1}t\right) e^{-\zeta_a\omega_a t} \right) \right). \quad (\text{A-5})
\end{aligned}$$

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