Removal of Co-Frequency Powerline Harmonics From Multichannel Surface NMR Data

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***Abstract*— Powerline harmonics are often the primary noise source in surface nuclear magnetic resonance (NMR) measurements. State-of-the-art techniques, such as notch filtering, Wiener filtering, and model-based subtraction, have been demonstrated to greatly mitigate powerline harmonic noise, but these approaches break down when one of the powerline harmonics has a frequency close to or coincident with the Larmor frequency f_L, referred to as a co-frequency harmonic. We propose a hybrid scheme where model-based subtraction of powerline harmonics is coupled with data from a synchronous reference coil to specifically subtract the co-frequency harmonic component. In standard model-based subtraction of powerline harmonics, a sinusoidal model of all harmonic components is fit to the data and subtracted. In the new approach, the amplitude and phase of the co-frequency harmonic are determined by a sinusoidal model fit to the synchronous noise-only data recorded in a reference coil. From the reference coil co-frequency model, the co-frequency harmonic in the primary coil is estimated using relationships between the amplitude and phase of the co-frequency harmonic in the two coils established during noise-only segments. By utilizing data from the reference coil to model the co-frequency harmonic, accidental fitting of the surface NMR signal is avoided. We investigate the efficiency of the method using a synthetic surface NMR signal embedded in noise-only data recorded in Denmark. Our results demonstrate that the co-frequency powerline harmonic can be removed efficiently without distorting the surface NMR signal and the new method performs better than standard methods.**

***Index Terms*— Co-frequency noise, model-based subtraction, powerline harmonics, reference coil, surface nuclear magnetic resonance (NMR).**

I. Introduction

Surface nuclear magnetic resonance (NMR) allows water resources in the near surface to be noninvasively quantified. This technique provides depth-resolved measurements of water content and NMR relaxation times, which are linked to hydrological parameters [1]. Surface NMR has successfully been applied in many countries worldwide and is continuously being improved with new hardware designs [2], transmitter pulse designs [3], data processing [4], [5], and inversion methods [6], [7]. One challenge of surface NMR is the low signal amplitude. This makes it extremely difficult to conduct measurements in many areas of interests where the local noise is too strong. A major noise component in the surface NMR measurements is powerline harmonics, i.e., sinusoidal signals at the powerline frequency and integer multiples thereof. Measurements conducted in the vicinity of electrical infrastructure are often completely dominated by powerline harmonics. Several methods for suppression of powerline harmonics have been proposed and successfully applied including notch filtering [8], adaptive noise canceling and Wiener filtering [2], [4], [9], and model-based subtraction [5]. A problem common to these approaches is that they can break down when one of the powerline harmonics has a frequency close to or coincident with f_L, a situation we refer to as a co-frequency harmonic, f_{co}. If this issue is neglected, both the amplitude and relaxation time of the surface NMR signal can be distorted by processing and lead to erroneous estimates of water content and hydrological parameters.

In this letter, we focus on model-based subtraction of powerline harmonics. Recent works have shown that model-based subtraction is an efficient method of mitigating the powerline harmonics, even in high-noise environments [5], [10]. Furthermore, as model-based subtraction removes only one specific noise component from the complex multisource noise environment, it makes the problem of establishing transfer functions for subsequent multichannel Wiener filtering easier [5]. One key obstacle for model-based subtraction is that the model-based algorithm cannot distinguish between the surface NMR signal and the co-frequency harmonic if their frequencies are close. In this limit, model-based subtraction approach may accidentally fit the surface NMR signal, i.e., misidentifying it as the co-frequency component and subtract it, leading to incorrect signal amplitudes and relaxation times. This issue can be reduced if the co-frequency model is determined on late parts of data where the NMR signal has decayed. The resulting co-frequency model can then be extrapolated to earlier times to avoid fitting the NMR signal [5]. This approach is valid as long as the powerline noise is stationary or very near-stationary. However, this assumption does not always hold in practice.

We propose a hybrid method to remove the co-frequency harmonic, where the model-based approach is extended using a reference coil. The method requires a multichannel surface NMR instrument, where one primary coil measures the NMR signal and one or more reference coils measure only noise. Reference coils provide synchronous records of noise which can be subtracted from the signal in the primary coil to give a noise reduced signal [2], [4], [9]. The amplitude and phase of the co-frequency harmonic are determined by a sinusoidal model fit to the noise-only data recorded in a reference coil.

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From the reference coil co-frequency model, the co-frequency harmonic in the primary coil is estimated using relationships between the amplitude and phase of the co-frequency harmonic in the two coils. These relationships are established during noise-only segments of data prior to the time series containing the surface NMR signal. By utilizing data from the reference coil to model the co-frequency harmonic, accidental fitting of the NMR signal is avoided. Our analysis is conducted with synthetic NMR signals superimposed on noise-only records and focuses on the ability to correctly retrieve the surface NMR signal. Our results show that the proposed method can remove the co-frequency harmonic without distorting the surface NMR signal and the accuracy is better than standard model-based subtraction.

This letter is organized as follows. Section II establishes the theoretical background for the model-based removal of co-frequency harmonics. Section III describes the measurement setup with two synchronous coils. Section IV analyzes the temporal variation of powerline harmonics and presents results obtained with synthetic surface NMR signals. The conclusion and final remarks follow in the last section.

II. Powerline Harmonic Subtraction

The signal recorded in the primary coil of a multichannel surface NMR instrument can be decomposed into four components [5]

$$p(k) = \mathrm{NMR}(k) + h_p(k) + s_p(k) + N_p(k). \tag{1}$$

Here, k is the sample number and NMR(k) denotes the NMR signal from the protons in subsurface. Powerline harmonic noise is described by $h_p(k)$, spikes by $s_p(k)$, and $N_p(k)$ represents all other noise components. The same decomposition into powerline harmonics, spikes, and other noise components can also be done for the signals measured in the reference coil(s)

$$r(k) = h_r(k) + s_r(k) + N_r(k). \tag{2}$$

A. Powerline Harmonic Modeling

Powerline harmonics can be modeled as sinusoidal signals whose frequencies are integer multiples of the same underlying fundamental powerline frequency f_0

$$h(k) = \sum_m A_m \cos\left(2\pi m \frac{f_0}{fs}k + \phi_m\right). \tag{3}$$

Here, f_s denotes the sampling frequency and the summation extends over all excited harmonic components. The determination of model parameters in (3) is a nonlinear optimization problem. For convenience, each term in (3) is rewritten as

$$A_m \cos\left(2\pi m \frac{f_0}{fs}k + \phi_m\right) = C_{m_1} \cos\left(2\pi m \frac{f_0}{fs}k\right) + C_{m_2} \sin\left(2\pi m \frac{f_0}{fs}k\right). \tag{4}$$

For an assumed f_0, C_{m_1}, and C_{m_2} are obtained by solving the linear equation with a standard least-square approach [11]. The best f_0 estimate is found by minimizing the energy of remaining noise after removal of the powerline harmonics. For computational efficiency, dichotomy can be employed based on the decreasing behavior of power of remaining noise when f_0 approaches its optimum value [5]. This method can be used to determine amplitudes and phases for all powerline harmonics measured in the primary coil and reference coil(s). Due to the fact that the powerline fundamental frequency and the distribution of harmonics is continuously varying, the model parameters are determined by using time-series segments with a duration of typically 1 s. Once the powerline harmonic model is determined, it is subtracted from the measured data to produce a noise reduced data set.

B. Co-Frequency Harmonic

In the presence of a co-frequency harmonic with $f_{\mathrm{co}} = qf_0 \approx f_L$, the NMR signal in the primary coil will be incorporated into the harmonic model and erroneously subtracted. To circumvent this problem, we propose an approach where powerline harmonics are fit on synchronous segments of data from the primary coil and a reference coil. For simplicity, only a single reference coil is considered here. First, a reduced model explicitly discounting the qth co-frequency harmonic is used for the primary coil

$$h_{p,\tilde{q}}(k) = \sum_{m \neq q} A_m \cos\left(2\pi m \frac{f_0}{fs}k + \phi_m\right). \tag{5}$$

Next, the powerline noise in the reference coil is fit using

$$h_r(k) = \sum_m B_m \cos\left(2\pi m \frac{f_0}{fs}k + \theta_m\right). \tag{6}$$

By subtraction of $h_{p,\tilde{q}}(k)$ and $h_r(k)$ from the two segments results in reduced noise records for both the primary and reference coils. The remaining qth component in the primary coil data with parameters A_q and ϕ_q

$$h_{p,q}(k) = A_q \cos\left(2\pi q \frac{f_0}{fs}k + \phi_q\right) \tag{7}$$

is estimated from the synchronous model of $h_{r,q}$ with

$$h_{r,q}(k) = B_q \cos\left(2\pi q \frac{f_0}{fs}k + \theta_q\right). \tag{8}$$

The relationships between the qth component in the primary and reference coil are given by

$$A_q = \alpha B_q \tag{9}$$

$$\phi_q = \beta + \theta_q \tag{10}$$

where the amplitude ratio α and phase difference β are determined on noise-only segments of data recorded prior to the excitation pulse, as depicted in Fig. 1. Finally, $h_{p,q}(k)$ is subtracted from the primary coil data to give an NMR record devoid of all powerline harmonics. The relationships, α and β are sensitive to spatial changes in the local noise field at the receiver coils but insensitive to changes in the overall noise level. This leads to a more accurate and robust estimation of the co-frequency harmonic component and a corresponding improved noise reduction performance.

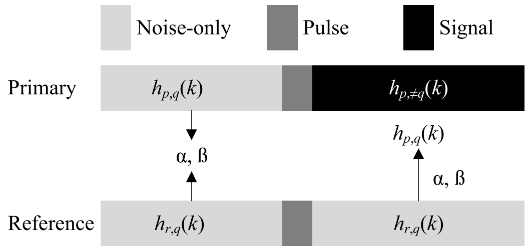

Fig. 1. Data sets consist of noise-only, pulse, and receiver segments in a primary coil and a reference coil in surface NMR measurements.

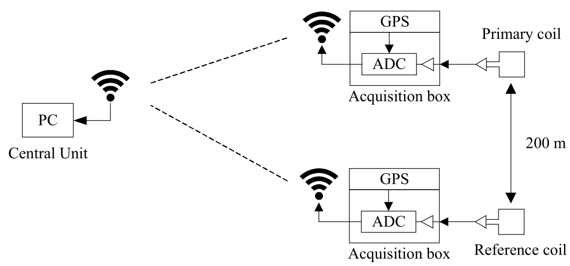

Fig. 2. Field setup for noise-only measurements with a primary coil and a reference coil separated by 200 m.

III. Experimental Setup

The measurements are performed with a multichannel surface NMR instrument with wireless connections between two receiver coils and a central unit as illustrated in Fig. 2. An ultralow noise preamplifier is directly connected to each coil and the signals are passed on to analog circuit, multistage amplifier boxes. Each box contains a 1–3-kHz bandpass filter to improve the signal-to-noise ratio before the signals are sampled at 31.25 kHz by a 24-bit analog-to-digital converter (ADC). All ADCs are driven by a GPS disciplined oscillator unit that outputs a fundamental 1-MHz clock and a time stamped one pulse-per-second trigger. The timing jitter between the two channels is less than 100 ns. Communication with a central unit and data transfer is achieved through a Wi-Fi connection. The receivers have an effective input noise level of 1.8 nV/$\sqrt{\text{Hz}}$ in the band of interest. Noise-only measurements were carried out 10-km west of Aarhus, Denmark. The site is close to infrastructure; a high voltage powerline is located 1 km to the east and buildings are located 500 m to the north. Two identical coils, denoted as primary and reference coils in the standard surface NMR terminology, both 10 m by 10 m, two-turn square loops were separated by 200 m. To investigate long-term variations in powerline harmonics, the measurement was carried out over 1.5 h.

IV. Results and Discussion

A. Analysis of Noise-Only Data

The noise-only data were analyzed in 1-s segments giving a resolution of approximately 1 mHz for the fundamental powerline frequency. Fig. 3(a) shows the changes in the fundamental frequency f_0 measured in the primary and reference coils over 1.5 h; the f_0 estimates in each coil are observed to track one another closely and cannot be visible discerned. The mean value and standard deviation of difference between the two f_0 estimates is 1.8×10^{-4} and 0.6 mHz during the measurement.

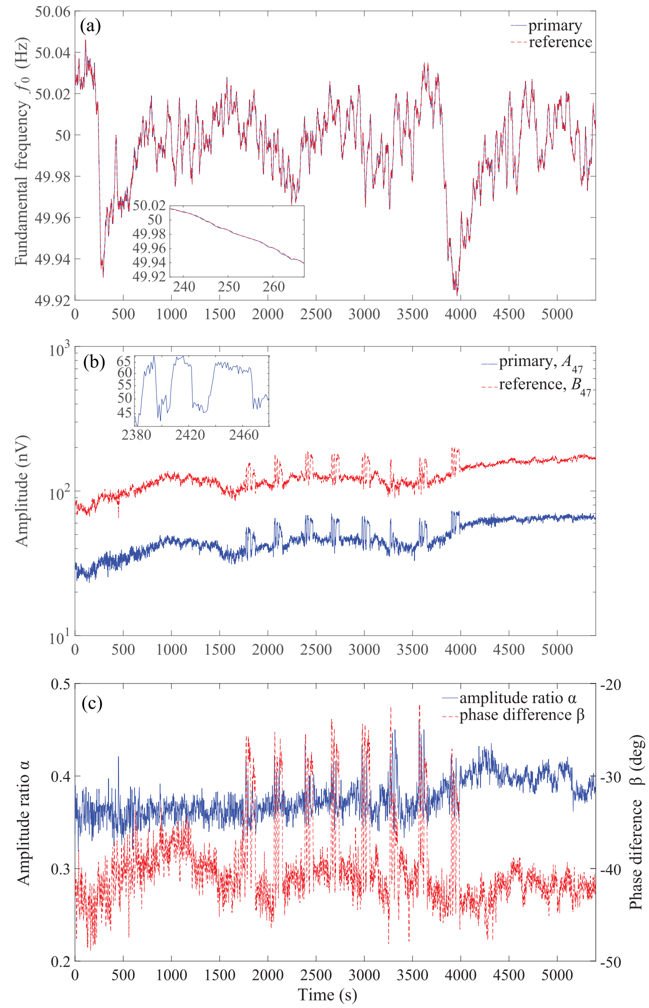

Fig. 3. Results of powerline harmonics recorded over 1.5 h in two coils. (a) Fundamental frequency f_0 of the powerline harmonics. (b) Amplitudes, A_{47}, B_{47} of the 47th harmonic. (c) Amplitude (α) and phase (β) relationships for the 47th harmonic.

Fig. 3(a) also highlights that f_0 is time-dependent and exhibits rapid random changes. For example, f_0 is observed to vary at 3.2 mHz/s from $t = 237$ s to $t = 267$ s [Fig. 3(a) inset]. For example, the 47th harmonic at 2350 Hz, this corresponds to a 0.15 Hz/s change. Fig. 3(b) illustrates the amplitude of the 47th harmonic at 2350 Hz measured in each coil. We observe that the amplitudes are not equal but they track one another. No correlation between fitting parameters has been found in our analysis. The amplitude curves show a growing tendency with time, starting from 30 nV and ending at 68 nV in the primary coil. The observed fluctuations less than 3 nV are mainly caused by instrument noise and ambient random noise. Several short bursts, where the f_{co} harmonic's amplitude is increased, lasting up to 20 s are observed from $t = 1800$ s to $t = 4000$ s. The events are observed in both coils and are likely due to large load variations in the power grid. The inset provides a zoom on three bursts. For these particular events, the amplitude is seen to increase by 60% over 1–2 s. For such nonstationary noise, the approach of modeling the qth harmonic on the late, signal-free part of the record and extrapolating to the entire record becomes invalid.

TABLE I

ESTIMATION ERRORS OF PARAMETERS OF THE 47TH HARMONIC WITH THE CO-FREQUENCY AND FITTING SIGNAL-FREE METHODS

		Co-frequency method	Fitting signal-free
ΔA_q (nV)	mean	0.002	0.062
	std	1.56	2.41
	max	8.82	24.23
$\Delta \phi_q$ (deg)	mean	−0.09	0.35
	std	2.16	7.48
	max	11.86	32.08
Δf_0 (mHz)	mean	-0.01	-0.02
	std	0.59	1.60
	max	2	6

Fig. 3(c) shows α and β for the 47th harmonic. Here, α and β are observed to vary more slowly than the amplitude and phase themselves. Compared with the abrupt change from second to second in the initial phase of data segments due to variation of the fundamental frequency f_0, the phase difference, β, is relatively stable. In most cases, α varies less than 3%, and β varies less than 3° over a few seconds. Instrument noise and external random noise degrade the smoothness of the curves. The relationships will be more stable on data sets where the co-frequency harmonic has a larger amplitude. At the time when the amplitude increases in bursts, the relative change of α was smaller than 15%, and the phase difference change was less than 15°. From these observations, we conclude that for measurements lasting less than a few seconds, α and β can be considered fixed.

B. Comparison of Noise Modeling

The performance to predict the co-frequency harmonic are compared between the proposed method and the extrapolation method [5]. In the later method, the co-frequency model is determined on signal-free parts of the time series and extrapolated to the signal containing parts. We use noise-only data prior to the segment of interest to avoid potential errors that may be introduced if the NMR signal has long relaxation times. To conduct the comparison, we first split the 1.5 h of noise-only data into 2700 segments. Each segment contains 2 s of synchronized noise-only data measured in both coils. The performance of each method is judged by its ability to estimate the co-frequency component in the second half of the segment. In the proposed method, α and β are determined using the first half of the segment, while B_q and θ_q are estimated using the second half of the segment in the reference coil. Given these four parameters, the co-frequency harmonic in the primary coil during the second half of the segment can be calculated using (7), (9), and (10). In the second method, we model the co-frequency harmonic in the first half of the segment using the primary coil and extrapolate this model forward into the second half of the segment. The true co-frequency parameters are produced by directly modeling the co-frequency component in the second half of the segment using (7). The results are shown in Table I. We observe that mean values, standard deviations, and maximum values of estimation errors obtained by the proposed method are all smaller than simply fitting the signal-free data and extrapolating to the signal part in the primary coil, labeled as fitting signal-free in the table.

C. Performance of Co-Frequency Harmonic Removal

We compare the ability to retrieve the surface NMR parameters in the presence of co-frequency harmonic for three methods: (A) standard model-based method, (B) fitting on the signal-free part of the time-series and extrapolating, and (C) the proposed approach combining model-based algorithm and synchronous reference coil data. Numerical experiments were carried out with a monoexponential synthetic signal

$$S(k) = S_0 e^{-\frac{kT}{T_2^*}} \cos(2\pi f_L kT + \psi). \quad (11)$$

S_0, T_2^*, and ψ are the initial amplitude, relaxation time, and phase of the surface NMR signal, respectively, and $T = 1/f_s$ is the sampling period. The parameters of the synthetic signal are $S_0 = 100$ nV, $T_2^* = 0.2$ s, and $\psi = 1$ rad.

The estimated NMR parameters after removal of the co-frequency component are compared against the true NMR parameters for each method. For method (A), the model-based approach treats the co-frequency harmonic in the exact same manner as all other harmonics. For methods (B) and (C), the co-frequency component is estimated using the same workflow as in the previous noise-only comparison. Updated values for the co-frequency parameters α and β are estimated for each segment. The only difference here is that the second half of each of the 2700 segments is now embedded with synthetic signal $S(k)$. The overall processing procedure is as follows: 1) bandpass filtering from 2200–2500 Hz; 2) removal of all but the 47th harmonic with the model-based method; 3) removal of the co-frequency harmonic with three different methods; 4) averaging of 27 segments to suppress random noise; 5) synchronous detection to obtain the envelope; and 6) monoexponential least-square fitting. The processing procedure is identical for each method, except for step 3). The above procedure was repeated 100 times for each synthetic Larmor frequency to provide statistics about each method's performance. Fig. 4 shows the estimated amplitudes and relaxation times for a range of Larmor frequencies. That is, the Larmor frequency of the NMR signal embedded into each of the 2700 segments is manipulated and the entire workflow repeated to form a single column in each subfigures of Fig. 4. The shading implies the number of the estimated values located in the corresponding bins. Accurate performance is described by narrow histograms, centered about $S_0 = 100$ nV and $T_2^* = 0.2$ s. Deviation from the true values (observed by lighter gray color) corresponds to reduced performance. For the standard model-based subtraction approach [Fig. 4(a)], the estimated amplitude is significantly distorted when the Larmor frequency approaches $f_{co} = 2350$ Hz. This occurs because the model mistakes the synthetic signal for co-frequency harmonic. The estimated relaxation times in this case show a similar distortion [Fig. 4(d)]. In contrast, both the proposed method and the extrapolation method yield much better S_0 and T_2^* estimates. They both remove the co-frequency

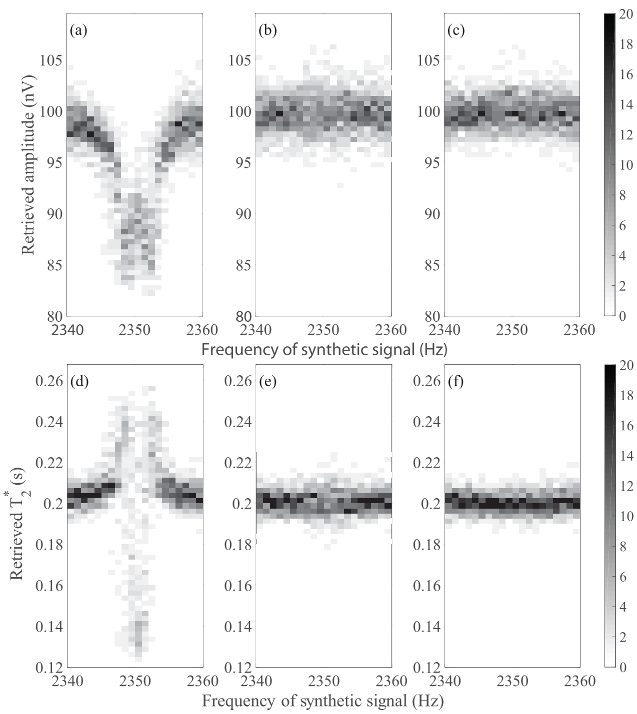

Fig. 4. (Top) Plot of retrieved S_0 and (Bottom) T_2^* as the Larmor frequency is scanned ±10 Hz at each side of 2350 Hz with three methods. (a) and (d) Standard model-based method. (b) and (e) Fitting on the signal-free part and extrapolating. (c) and (f) Co-frequency method.

harmonic without significant distortion of the surface NMR signal. However, the proposed method consistently produces more reliable S_0 and T_2^* estimates. This is observed by noting that the right column exhibits narrower histograms when the Larmor frequency and co-frequency are similar compared to the center column. For example, Fig. 4(b) shows a slight broadening when f_L approaches f_{co}. Furthermore, in some instances the estimated amplitudes exceed 103 nV or fall below 97 nV. Similar results are also found in Fig. 4(e). These poorly determined values are obtained when the co-frequency harmonic changes significantly during measurements.

To quantify the benefits of the proposed method, we calculated the uncertainty of the retrieved values. The proposed method consistently produces better estimates than method (B) for all investigated f_L. In the case when $f_L = 2350$ Hz, $S_0 = 100.16 \pm 1.56$ nV and $T_2^* = 0.208 \pm 0.004$ s with the co-frequency method, while they are 99.85 ± 2.89 nV and 0.213 ± 0.012 s with method (B). With the proposed method the root-mean-square noise level is reduced from ∼400 nV in unprocessed field data to ∼8 nV after processing and stacking. The retrieved values after removal of the co-frequency harmonic using the proposed method are more accurate and exhibit smaller standard deviations. In experiments using other parameters of the synthetic signal, we obtain similar improvements in performance. When the co-frequency harmonic is stationary, both the proposed method and the method fitting on signal-free time-series are effective at removing the co-frequency harmonic without distorting the surface NMR signal. The major advantage of the proposed approach is that even in the presence of significant changes in the co-frequency harmonic, reliable estimates of the NMR signal can still be produced.

V. Conclusion

We have investigated a new method of removing the co-frequency harmonic from surface NMR measurements. The method combines model-based subtraction and reference coil techniques to subtract the noise component associated with a powerline harmonic near the Larmor frequency. The method relies on the assumption, that even if the noise is rapidly varying, it does so similarly in both the primary and the reference coil. As such, the relation between noise components measured in the primary and reference coils is much more stable. Numerical experiments with synthetic signals show that the method can mitigate the co-frequency harmonic efficiently without distorting a synthetic surface NMR signal, even in the challenging limit where the Larmor frequency overlaps with a powerline harmonic. The new method gives more robust estimates of amplitude and relaxation than the current approaches of fitting the co-frequency harmonic on the later part of the data and extrapolating. In turn, this translates directly into more precise geologic models. The method will be particularly useful in scenarios where the noise changes significantly over short time spans. As the co-frequency method relies on the reference coil data, it can easily be combined with Wiener filtering, which at many sites will lead to further noise reduction.

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