MRS2015 / 6th International Workshop on Magnetic Resonance

Signal processing tutorial

or

How can the signal to noise ratio of surface NMR measurements be increased with post-processing of data?

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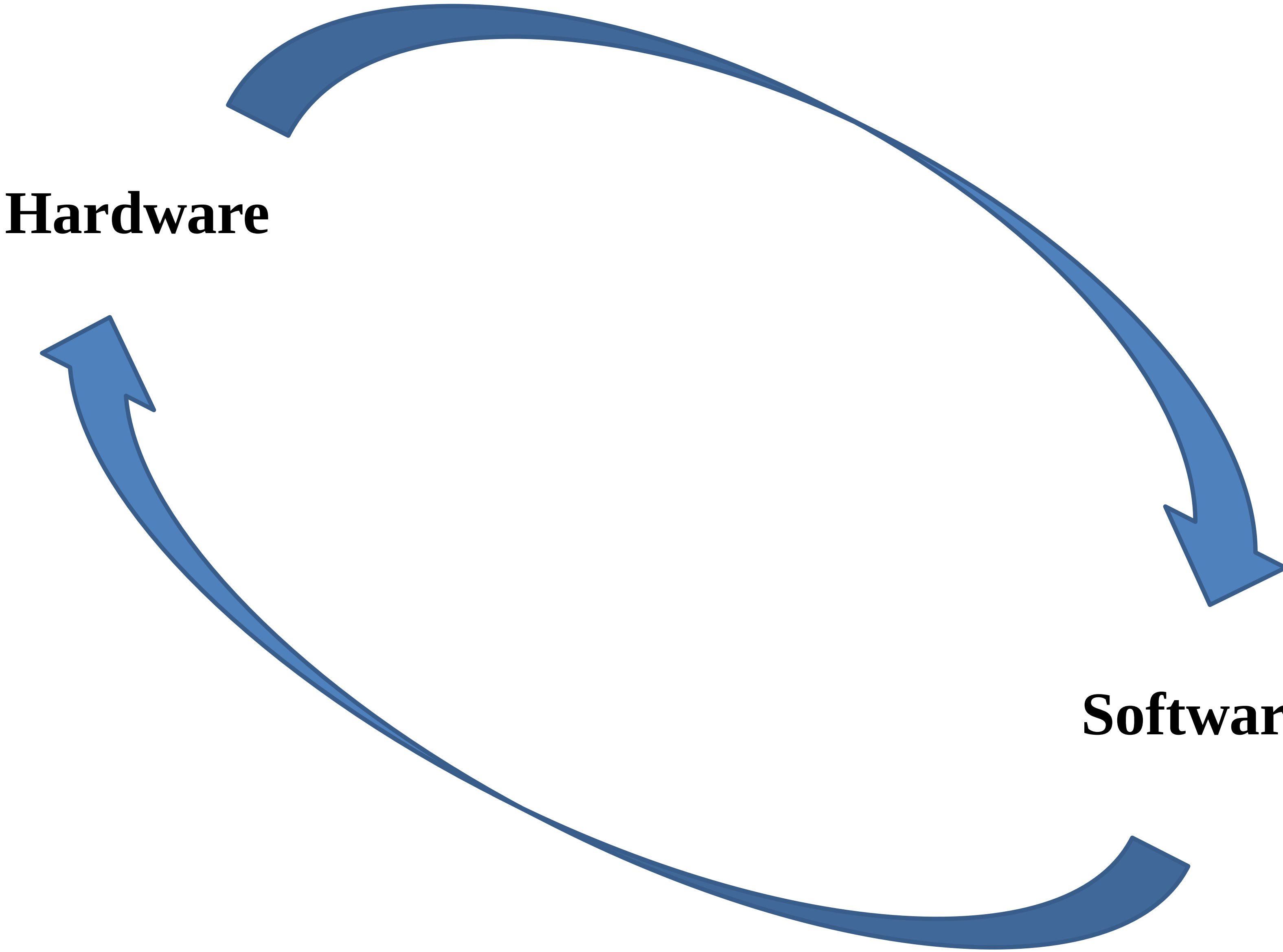
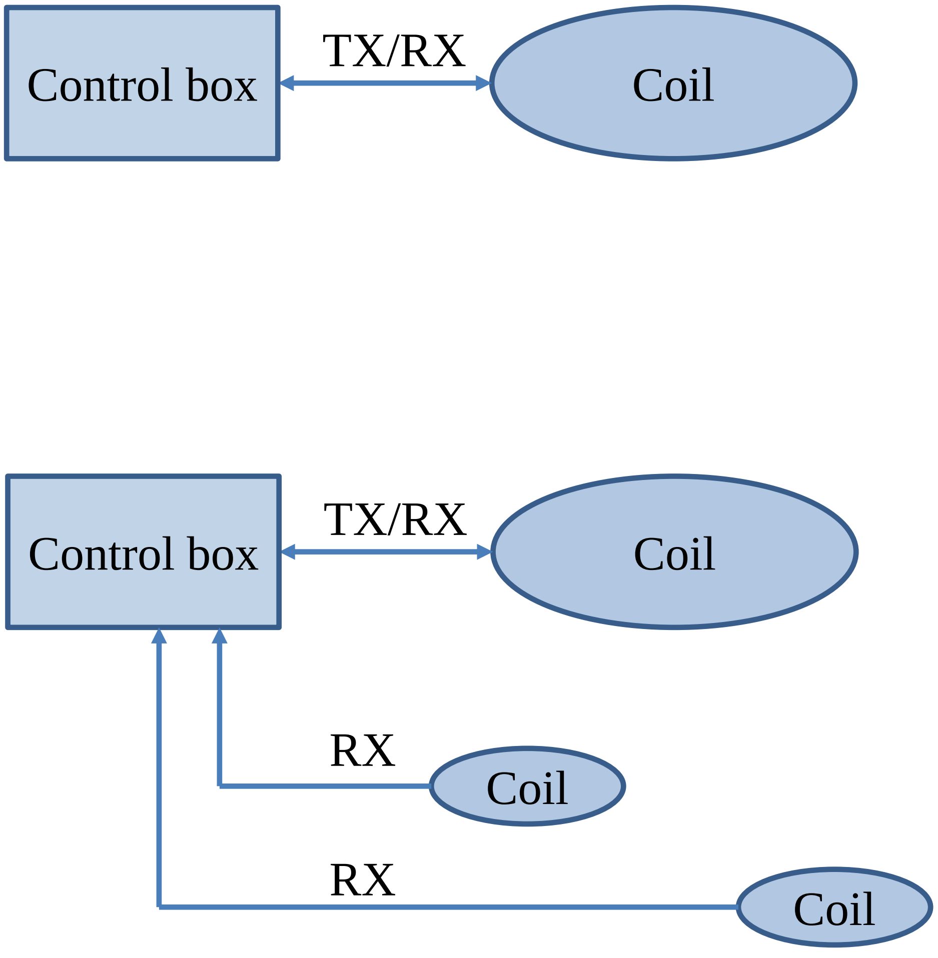
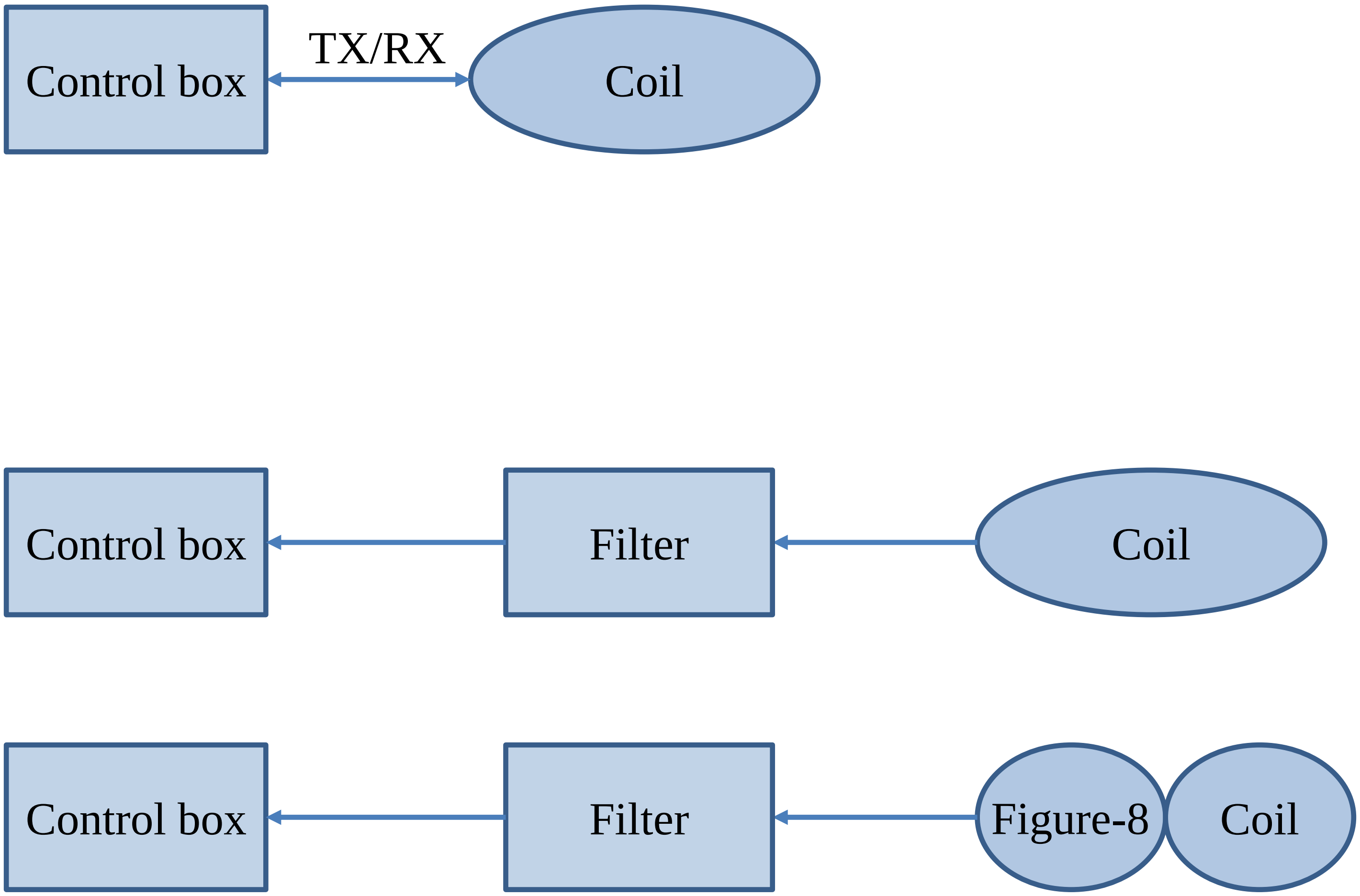

Hardware
Software

Single channel and multichannel surface NMR instruments



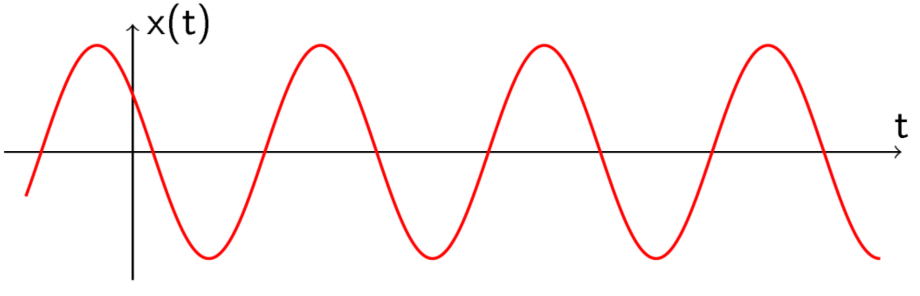
Hardware noise reduction

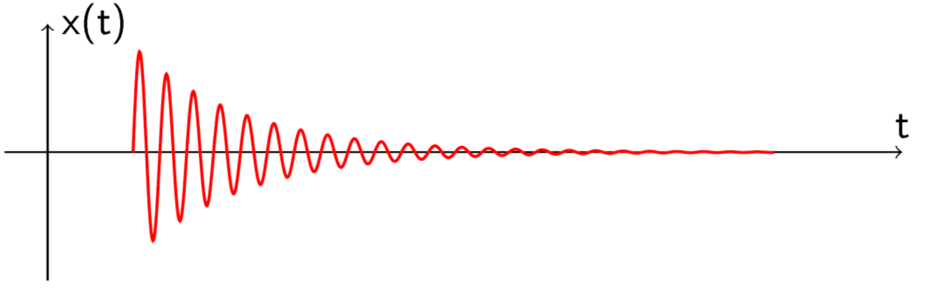


Signal Classification

Energy signals: $\int_{-\infty}^{\infty} x^2(t)dt < \infty$

Power signals: $\int_{-\infty}^{\infty} x^2(t)dt$ is infinite, but $\frac{1}{2T}\int_{t_0}^{t_0+T} x^2(t)dt$ is finite





SNR - Signal to Noise Ratio

It is tricky to define an unambiguous and meaningful SNR

- The surface NMR signal is an energy signal
- Noise can be both energy signals and power signals

$$\text{SNR} = \frac{\text{Initial amplitude of surface NMR signal}}{\text{Root mean square of noise signal}}$$

Correlated and uncorrelated noise

- Correlation: Is there any **linear relationship** between the signal now and the signal a little later?

  Is there any **linear relationship** between the signal now and the signal in a different channel a little later?

$$E[x(t)x(t-\tau)] \neq 0$$

E = expectation operator

$$E[x(t)y(t-\tau)] \neq 0$$

Analogous expression for two channel signals

- Uncorrelated noise: Filtering and averaging
- Correlated noise: Other tricks are possible
- Multichannel correlated noise:

  Quantify using the (multiple) squared coherence function

Bendat & Piersol: Random Data, 4th edition, Wiley 2010

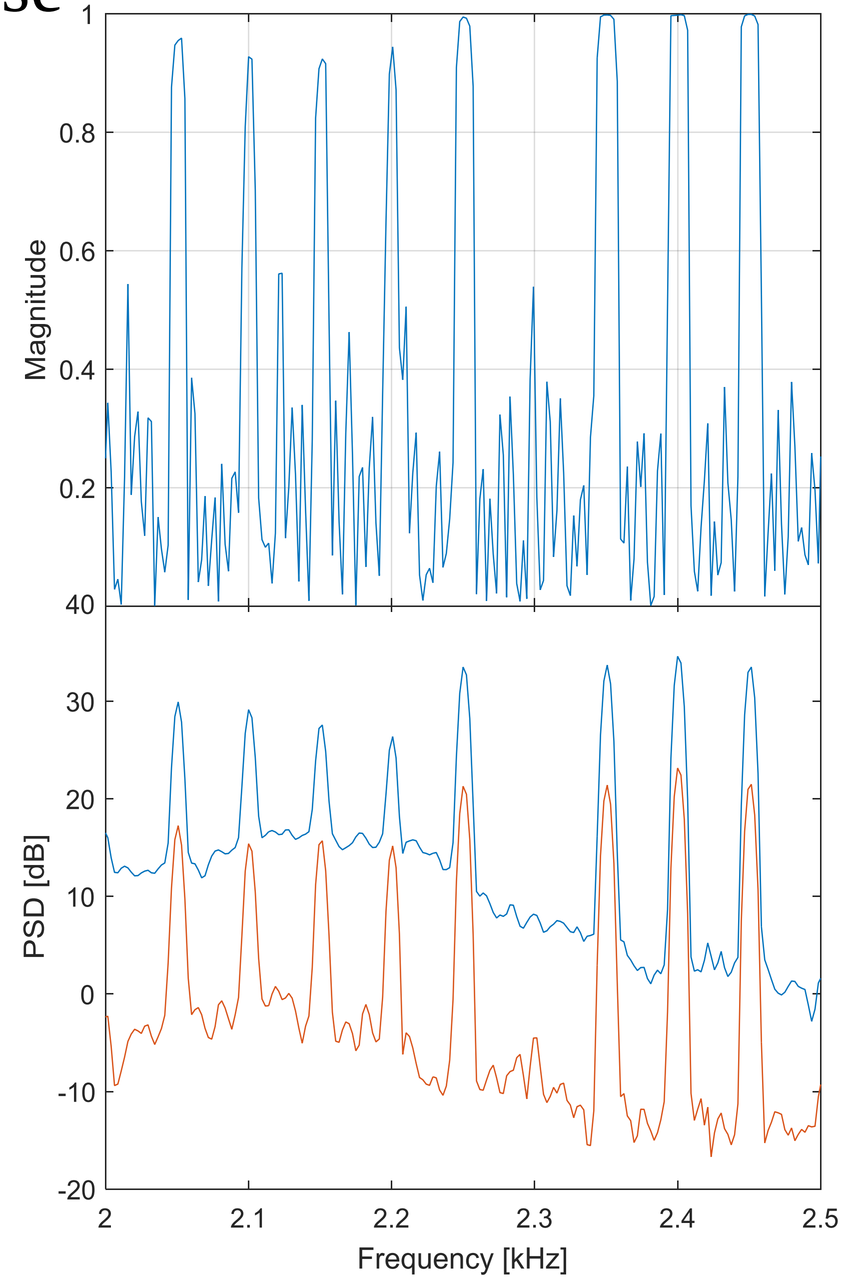
Correlated and uncorrelated noise

Magnitude square coherence function

(normalized correlation measure)

$$|\gamma_{xy}(f)|^2 = \frac{|S_{xy}(f)|_2}{S_{xx}(f)S_{yy}(f)}$$

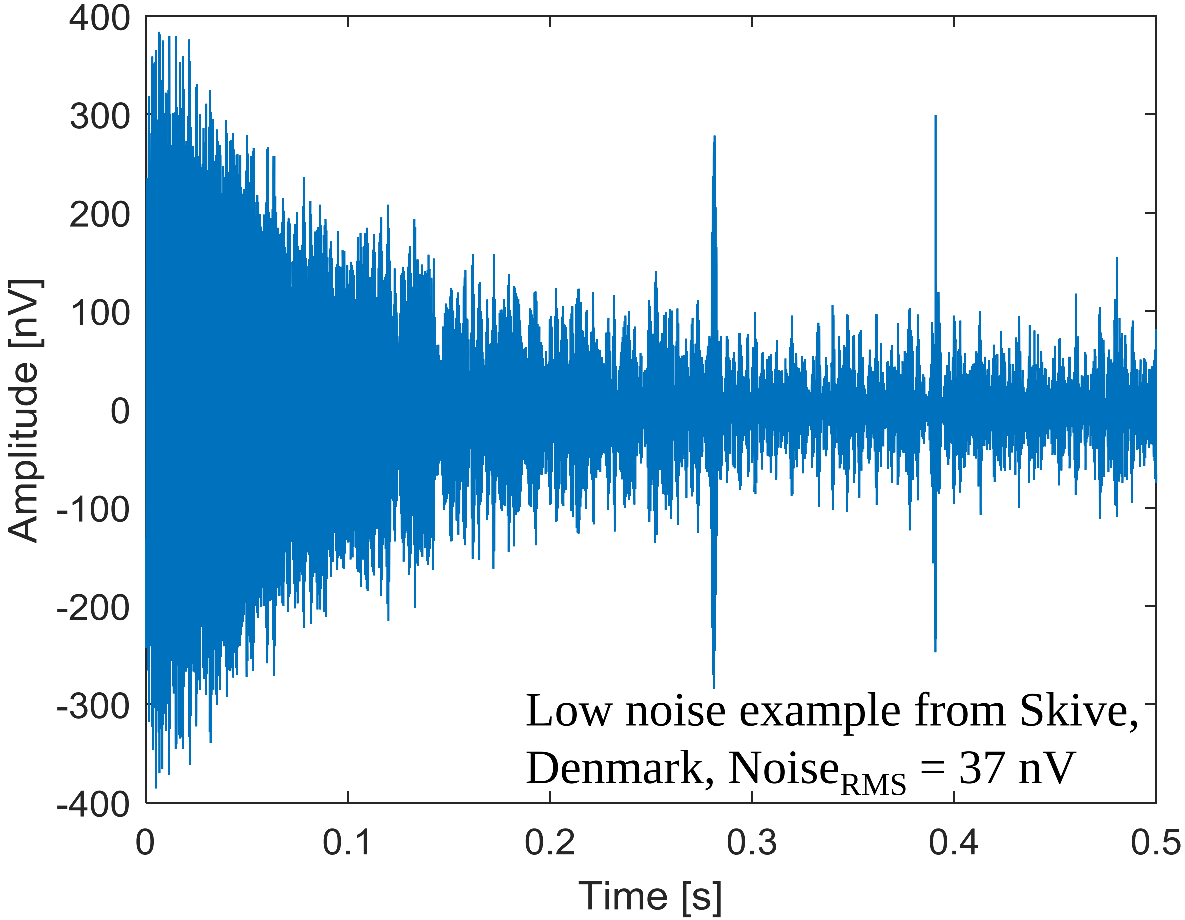
$$0 \leq |\gamma_{xy}(f)|^2 \leq 1$$



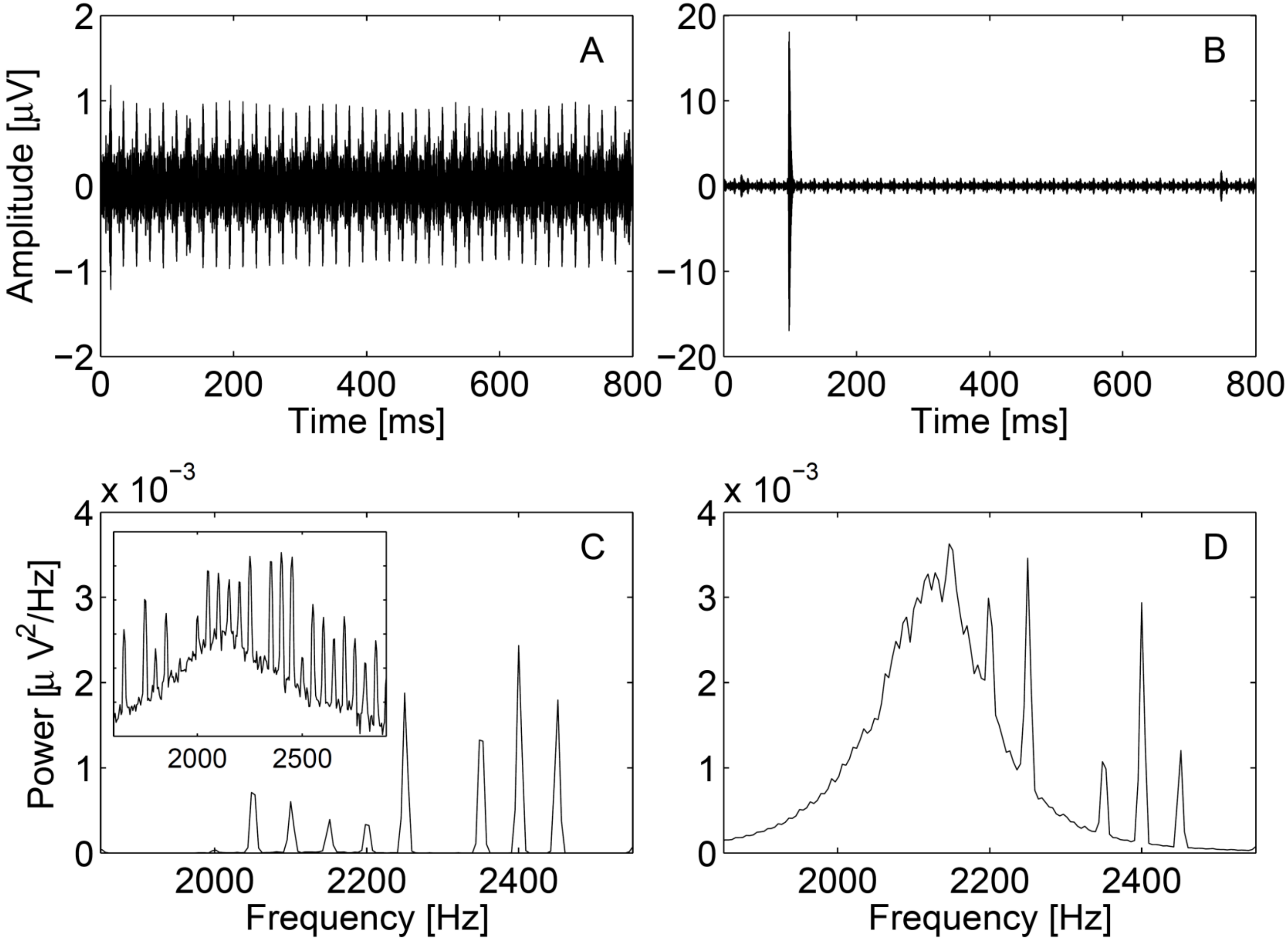
Examples of surface NMR data

The 'prototype' NMR signal is a decaying sinusoidal wave

$$NMR(t) = Ae^{-\frac{t}{T_2^*}}\cos(2\pi f_L t + \varphi)$$

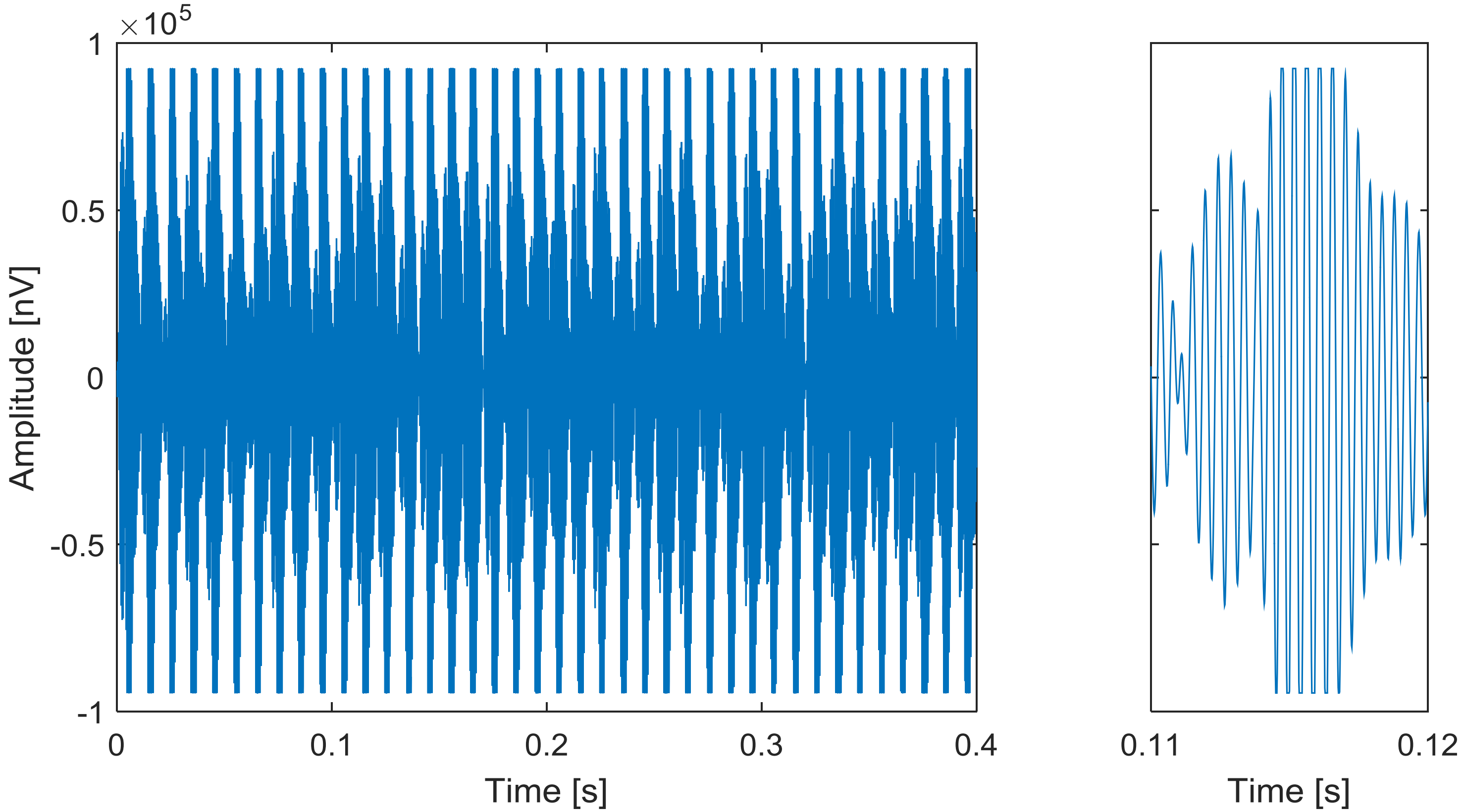


Examples of surface NMR data



Data from Odder, Denmark

Examples of surface NMR data



- Signal processing **breaks down** if the detector system is **nonlinear** (clipping / saturating)
  Data collected nearby a Denmark-Norway HVDC powerline

Classification of noise in surface-NMR

Powerline harmonics

50 Hz / 60 Hz, some electrical trains at $16\frac{2}{3}$ Hz
Nearly stationary

Impulsive noise / spikes

Electric fences
Sferics (thunderstorms)

Instrument noise

Amplifiers
ADC quantization noise

Other noise sources?

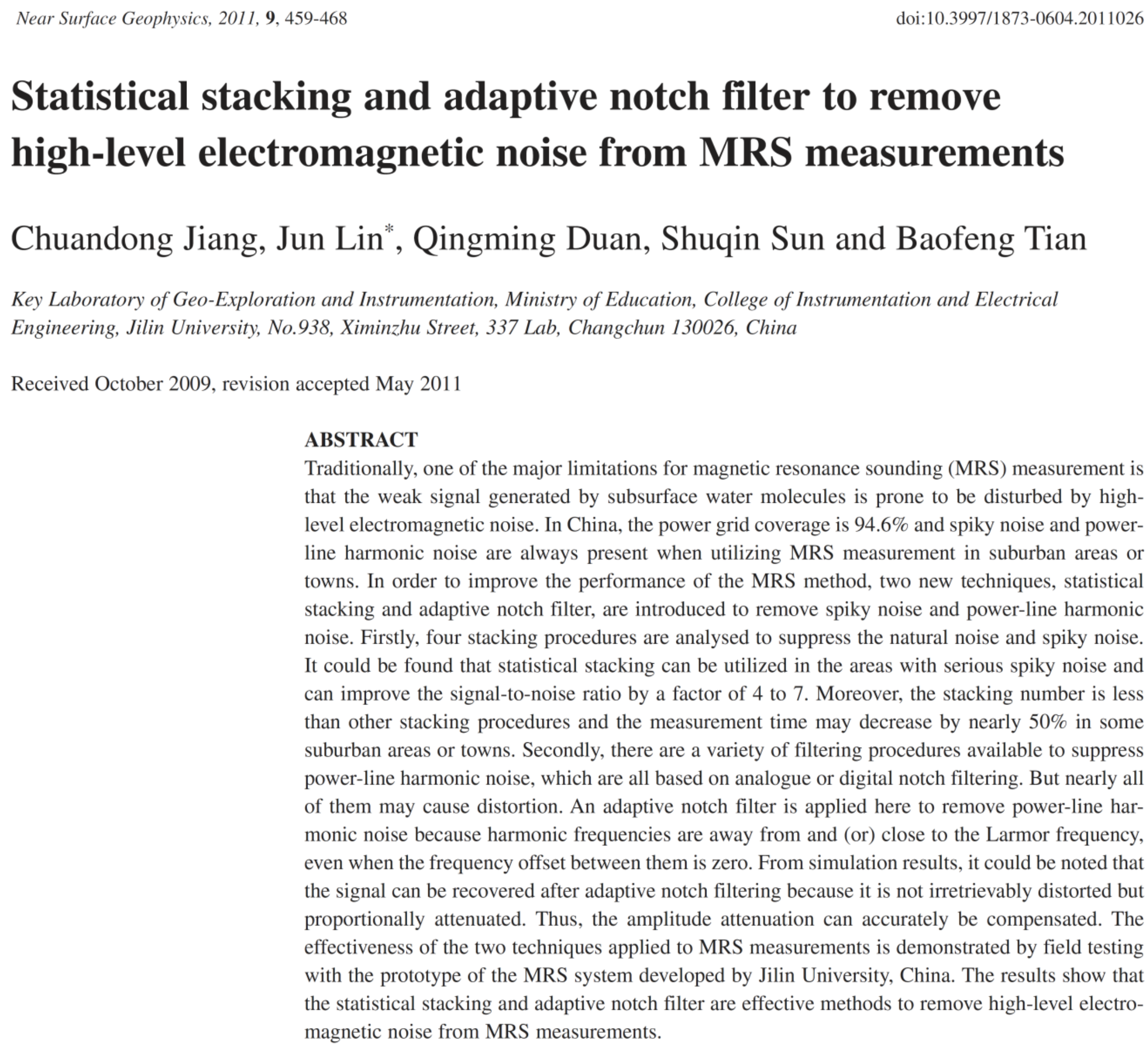
Stacking (averaging)

- The simplest way of reducing noise

$$SNR \propto \sqrt{N}$$ where N = number of stacks

- Incoherent / random noise is suppressed
- Synchronous noise, if present, will be enhanced!
- **Time consuming**
- More advanced stacking schemes possible – e.g. throw away outliers

Stacking (averaging)


Near Surface Geophysics, 2011, **9**, 459-468 doi:10.3997/1873-0604.2011026

Statistical stacking and adaptive notch filter to remove high-level electromagnetic noise from MRS measurements

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ABSTRACT

Traditionally, one of the major limitations for magnetic resonance sounding (MRS) measurement is that the weak signal generated by subsurface water molecules is prone to be disturbed by high-level electromagnetic noise. In China, the power grid coverage is 94.6% and spiky noise and power-line harmonic noise are always present when utilizing MRS measurement in suburban areas or towns. In order to improve the performance of the MRS method, two new techniques, statistical stacking and adaptive notch filter, are introduced to remove spiky noise and power-line harmonic noise. Firstly, four stacking procedures are analysed to suppress the natural noise and spiky noise. It could be found that statistical stacking can be utilized in the areas with serious spiky noise and can improve the signal-to-noise ratio by a factor of 4 to 7. Moreover, the stacking number is less than other stacking procedures and the measurement time may decrease by nearly 50% in some suburban areas or towns. Secondly, there are a variety of filtering procedures available to suppress power-line harmonic noise, which are all based on analogue or digital notch filtering. But nearly all of them may cause distortion. An adaptive notch filter is applied here to remove power-line harmonic noise because harmonic frequencies are away from and (or) close to the Larmor frequency, even when the frequency offset between them is zero. From simulation results, it could be noted that the signal can be recovered after adaptive notch filtering because it is not irretrievably distorted but proportionally attenuated. Thus, the amplitude attenuation can accurately be compensated. The effectiveness of the two techniques applied to MRS measurements is demonstrated by field testing with the prototype of the MRS system developed by Jilin University, China. The results show that the statistical stacking and adaptive notch filter are effective methods to remove high-level electromagnetic noise from MRS measurements.

Digital filtering

Data are **sampled** into the **digital domain**: $x(t) = x(nT_s) = x(n)$

"z-transform, the digital counterpart to the Fourier transform"

Filters are implemented as **difference equations**

$$y(n) = b_0 x(n) + b_1 x(n-1) + b_2 x(n-2) + \ldots \; - a_1 y(n-1) - a_2 y(n-2) \; - \; \ldots$$

Transfers functions relate input and output $Y(z)=H(z)X(z)$

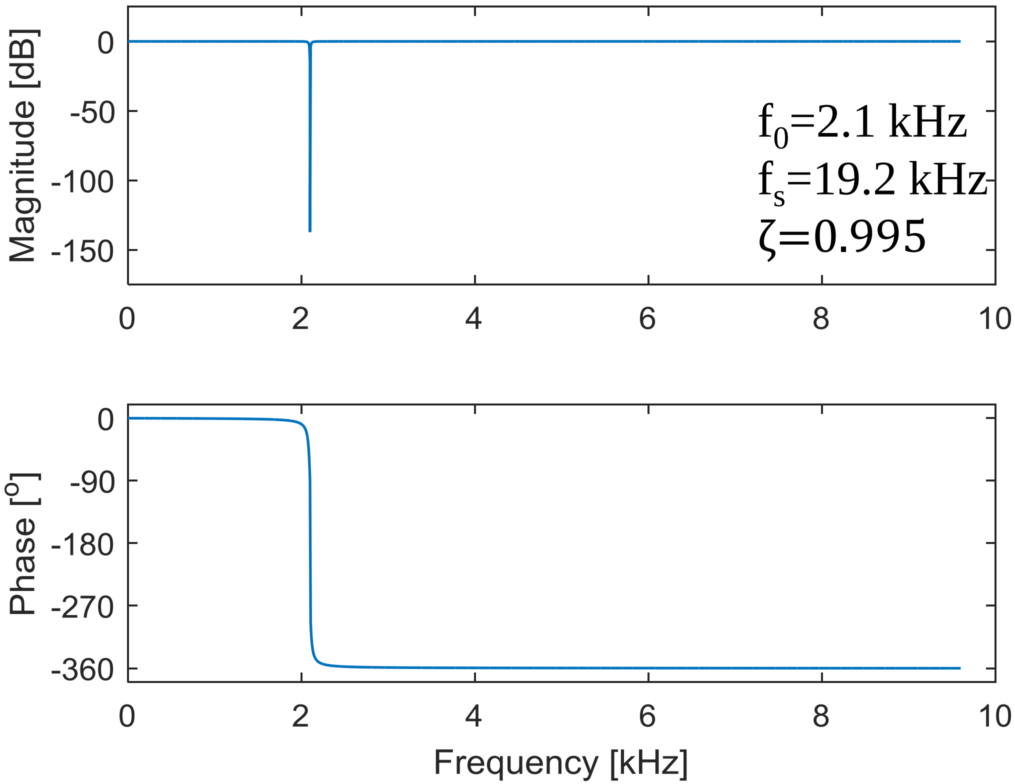
$$H(z) = \frac{b_0 + b_1 z^{-1} + b_2 z^{-2} + \cdots}{1 + a_1 z^{-1} + a_2 z^{-2} + \cdots}$$

Notch filtering

The transfer function of a 2nd order notch filter is given by

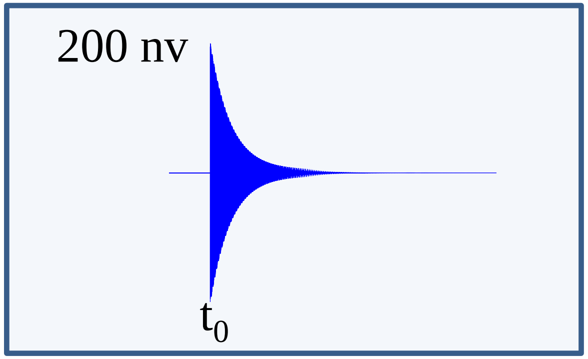
$$H(z) = \frac{1 - 2\cos(2\pi f_0/f_s)z^{-1} + z^{-2}}{1 - 2\zeta\cos(2\pi f_0/f_s)z^{-1} + \zeta^2 z^{-2}}$$

f_0 is the frequency of the notch and ζ controls the width of the notch

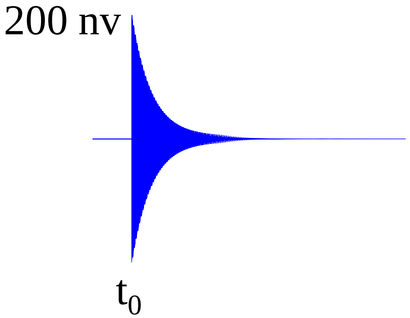


Notch filtering – A little quiz

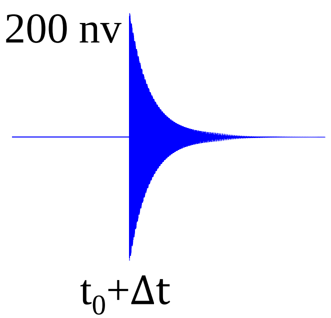
Assume we have an NMR signal with f_L=2108 Hz, T_2^*=50 ms, A=200 nV and apply a notch filter at 2100 Hz to remove a powerline harmonic. What is the effect on the NMR pulse?



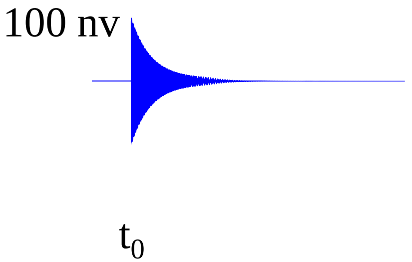
A: Nothing



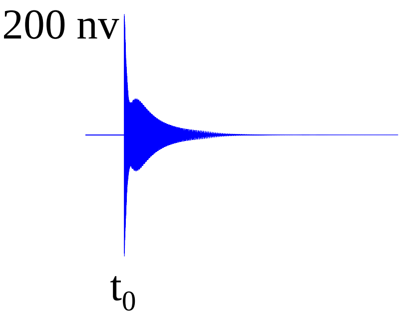
B: Delay



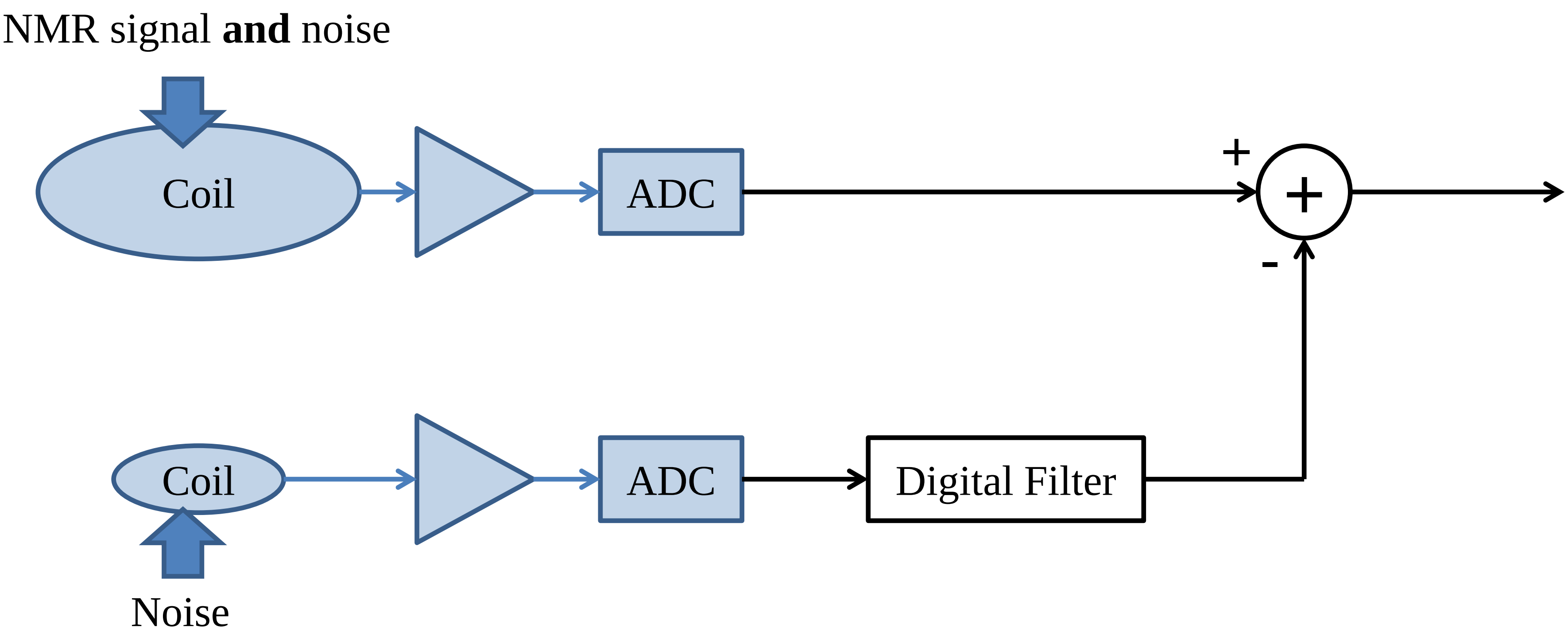
C: Attenuation



D: Distortion

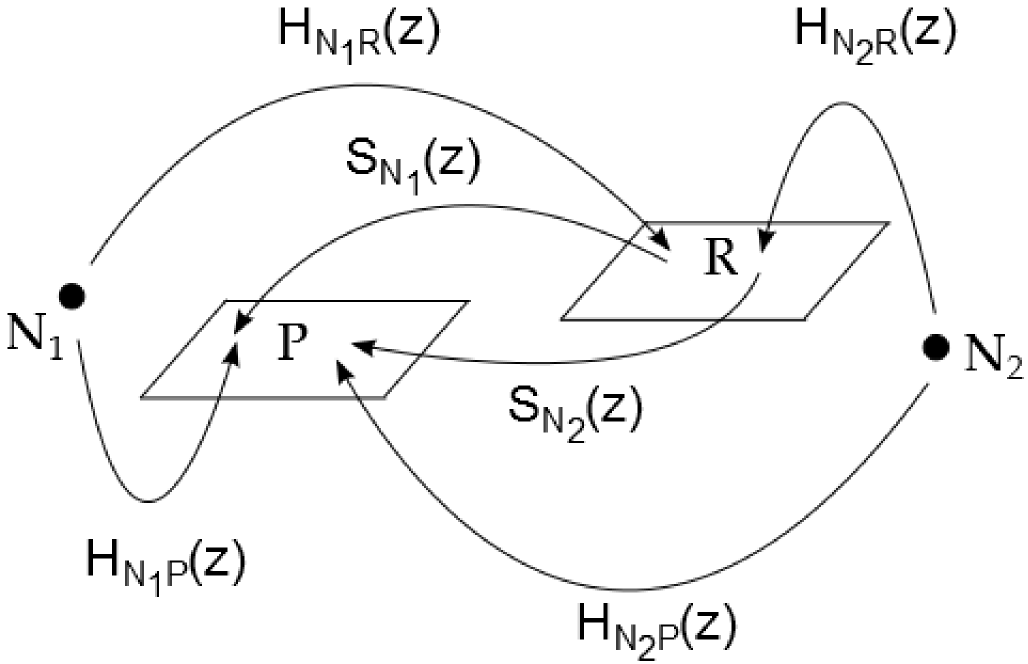


Multichannel filtering



Multichannel filtering in complex noise environments

- Primary coil and reference coil
- Two noise sources N_1 and N_2

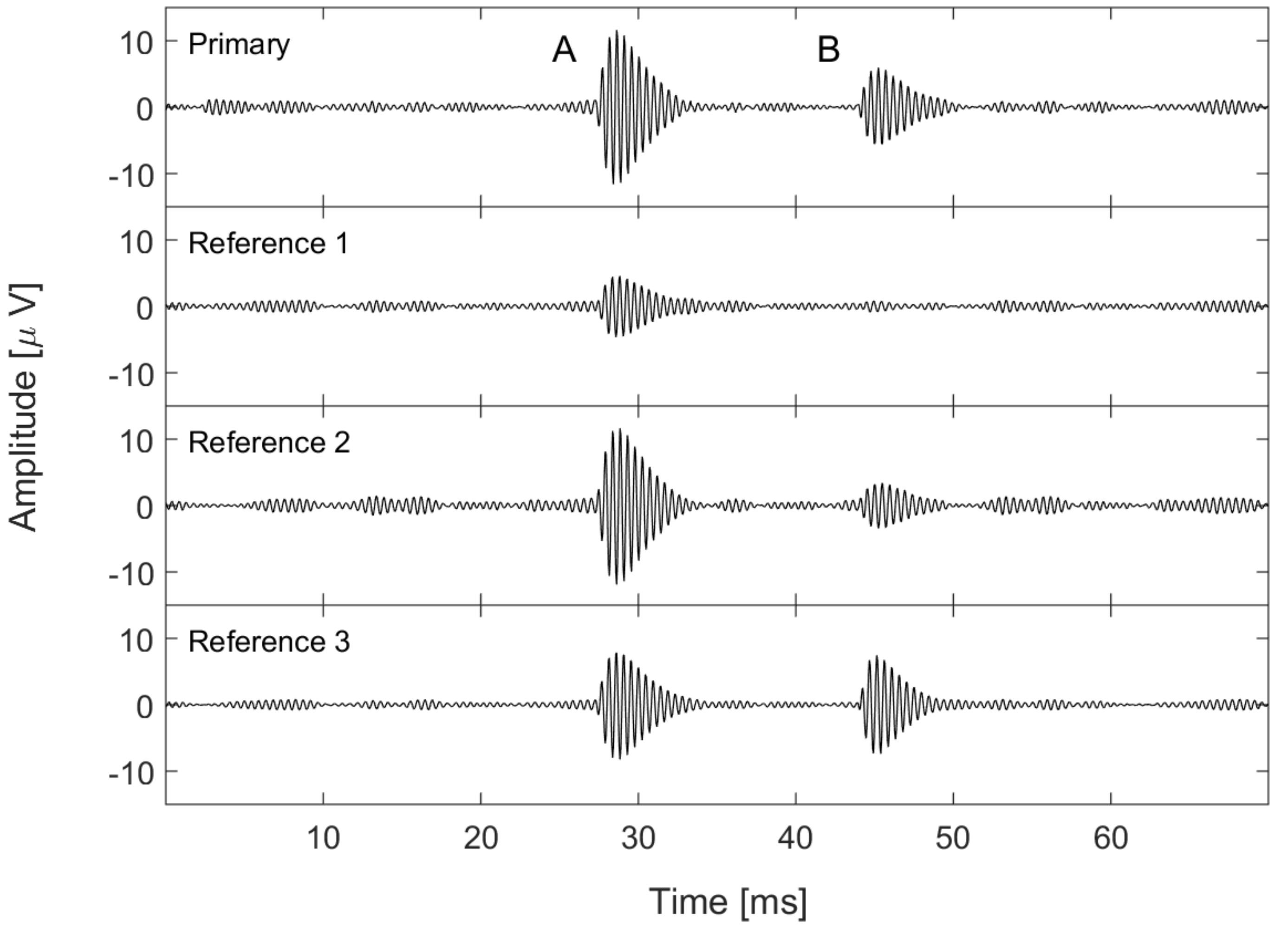


- The optimum noise cancelling transfer functions are given by

$$S_{N_1}(z) = \frac{H_{N_1P}(z)}{H_{N_1R}(z)} \qquad S_{N_2}(z) = \frac{H_{N_2P}(z)}{H_{N_2R}(z)}$$

And they are not necessarily equal!

Multichannel filtering in complex noise environments



Multichannel filtering

Near Surface Geophysics, 2014, **12**, 199-210 doi: 10.3997/1873-0604.2013033

Comparison and optimal parameter settings of reference-based harmonic noise cancellation in time and frequency domains for surface-NMR

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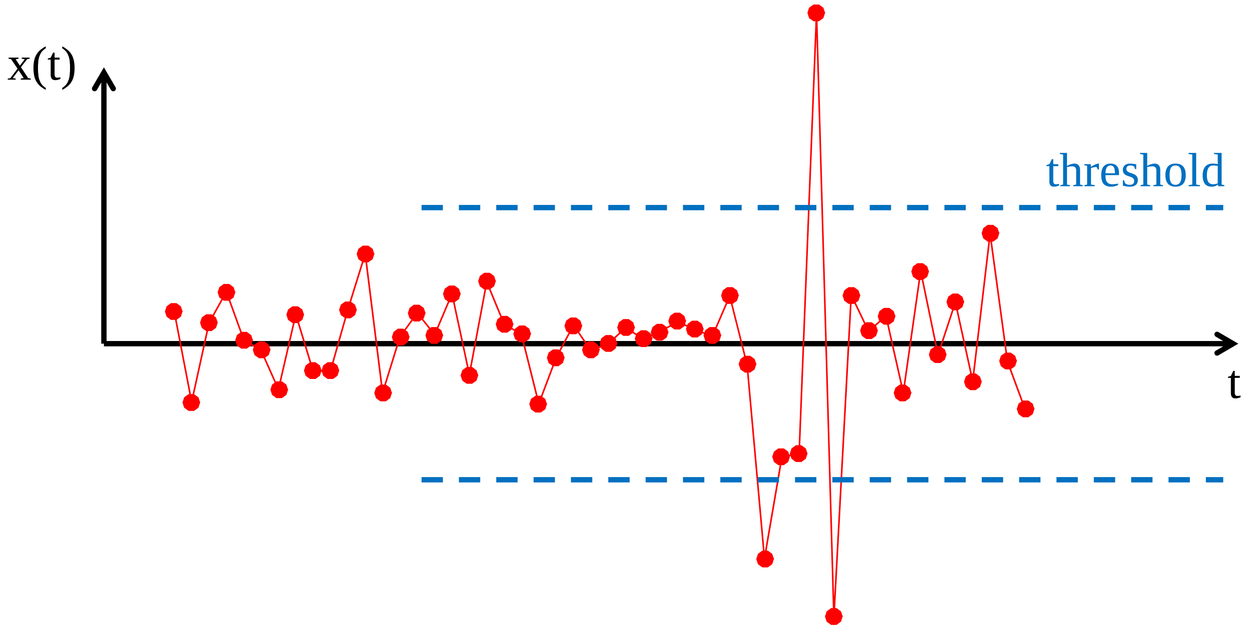
ABSTRACT

The technique of surface nuclear magnetic resonance (surface-NMR) provides information on porosity and hydraulic conductivity that is highly valuable in a hydrogeological context. However, the applicability of surface-NMR is often limited due to a bad signal-to-noise ratio. In this paper we provide a detailed insight into the technique of harmonic noise cancellation based on remote references to improve the signal-to-noise ratio. We give numerous synthetic examples to study the influence of various parameters such as optimal filter length for time- domain approaches or the necessary record length for frequency-domain approaches, all of which evaluated for different types of noise conditions. We show that the frequency-domain approach is superior to time-domain approaches. We demonstrate that the parameter settings in the frequency domain and the decision whether or not to use separated noise measurement depend on the actual noise properties, i.e., frequency content or stability with time. We underline our results using two field examples.

Despiking

- If spikes can't be removed using multichannel filtering other methods must be used
- To remove spikes they must first be identified through a (semi-)automatic process
- What makes a spike a spike?



- How do we remove a spike?

Despiking

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Despiking of magnetic resonance signals in time and wavelet domains

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ABSTRACT

In this paper three different despiking methods for surface-NMR data are investigated and compared. Two of these are applied in the time domain: a threshold is determined that identifies and marks a spiky event. Afterward, the marked time sequence is substituted with zeros or with the mean value of the signal amplitude of the measurement repetitions for the same passage on the time axis. The third despiking approach takes advantage of the wavelet-like nature of spiky events. It isolates and eliminates spiky signals in the wavelet domain, i.e., after transforming a single record with the help of the discrete wavelet transform. The latter is able to reconstruct the original signal content in the (spike-caused) distorted time sequence to some extent. If the spiky noise in surface-NMR measurements consists mainly of single spiky events, the three despiking methods show very similar results and are able to remove spiky noise from data very effectively, as we can show with two real data examples. However, a synthetic study shows that, if a series of spikes within a relatively short period of time occurs, the wavelet-based despiking approach shows significant shortcomings. Because the NMR signal content cannot be restored completely in a single record, the fitting of the signal after stacking leads to underestimation of the initial amplitude up to approximately 10%. Nevertheless, we can show that, in principle, the processing of surface-NMR data in the wavelet domain works and can lead to the same results as straight-forward applications. Moreover, wavelet-based strategies have some interesting properties and thus have some potential for further development regarding surface-NMR processing, which is discussed in detail.

Despiking - preemphasis

- Preemphasize spikes before thresholding

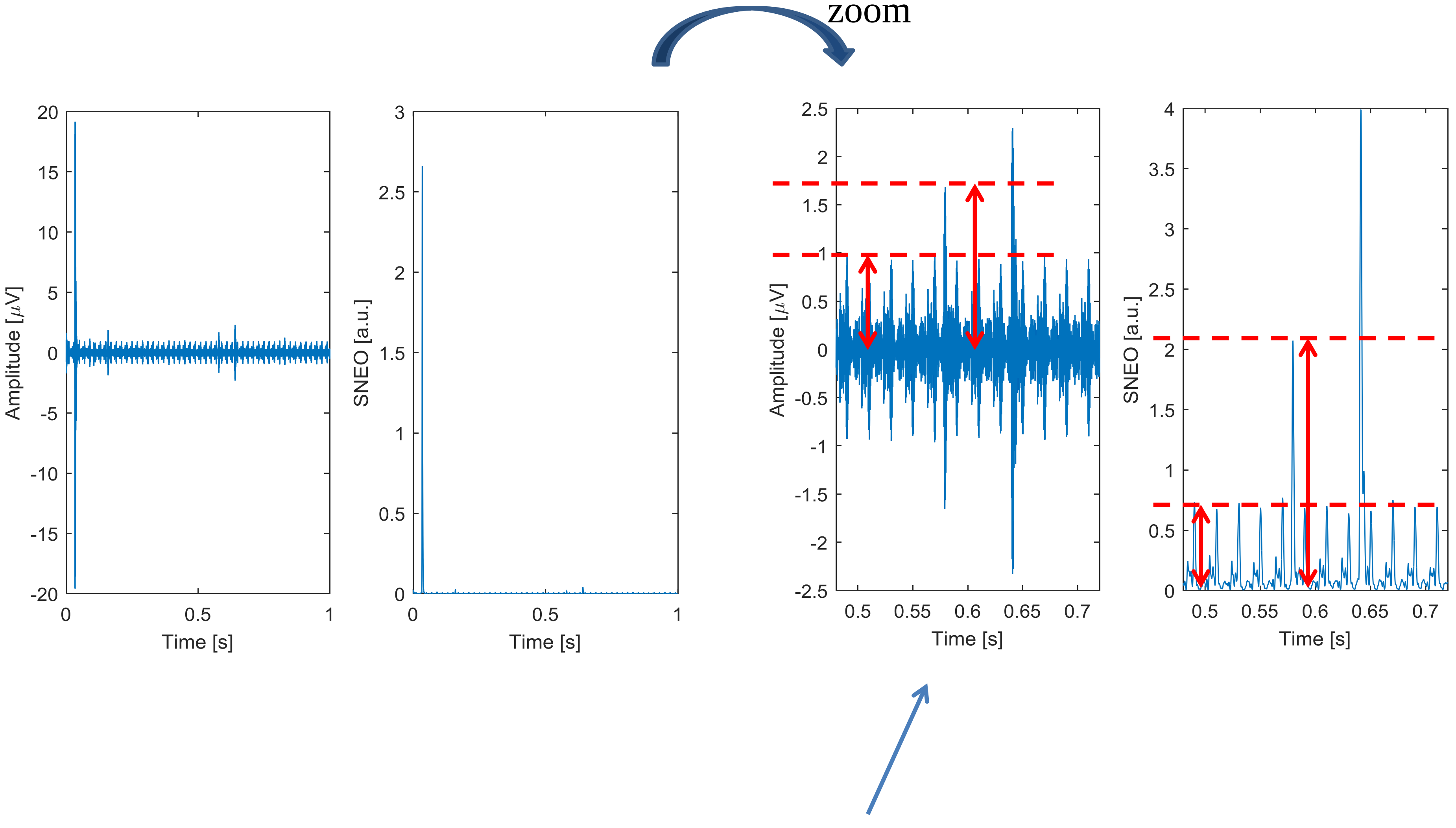
Nonlinear energy operator (NEO)(Teager-Kaiser)

$$y(n) = \varphi[x(n)] = x^2(n) - x(n+1)x(-1)$$

Smoothed nonlinear energy operator (SNEO)

$$y(n) = \varphi[x(n)] = Lowpass[x^2(n) - x(n+1)x(-1)]$$

Despiking - preemphasis

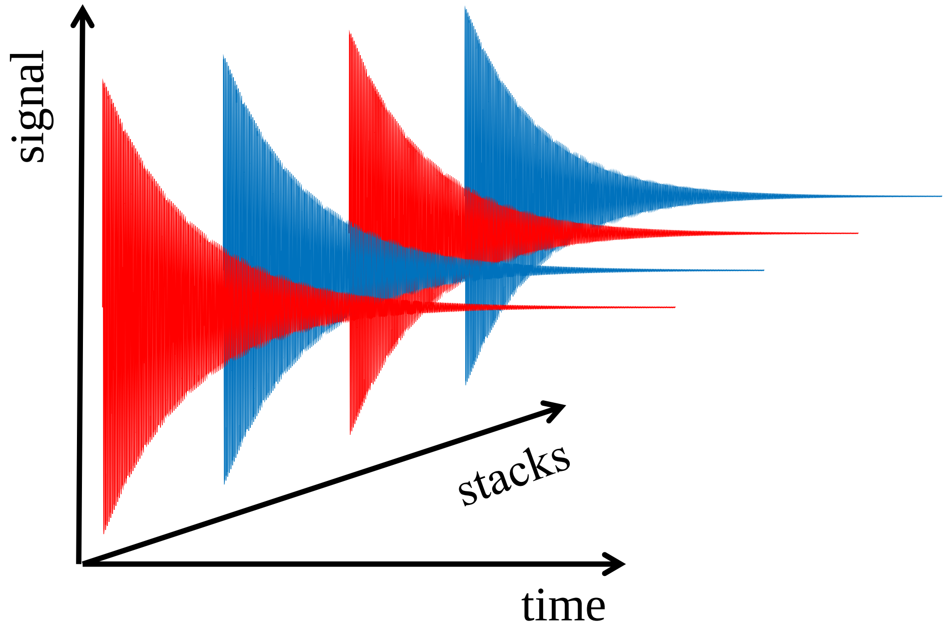


Improved peak to baseline ratio
with preemphasis

Despiking – ensemble based threshold

NMR signal is detected by SNEO

- Apply threshold along stacks instead of along time

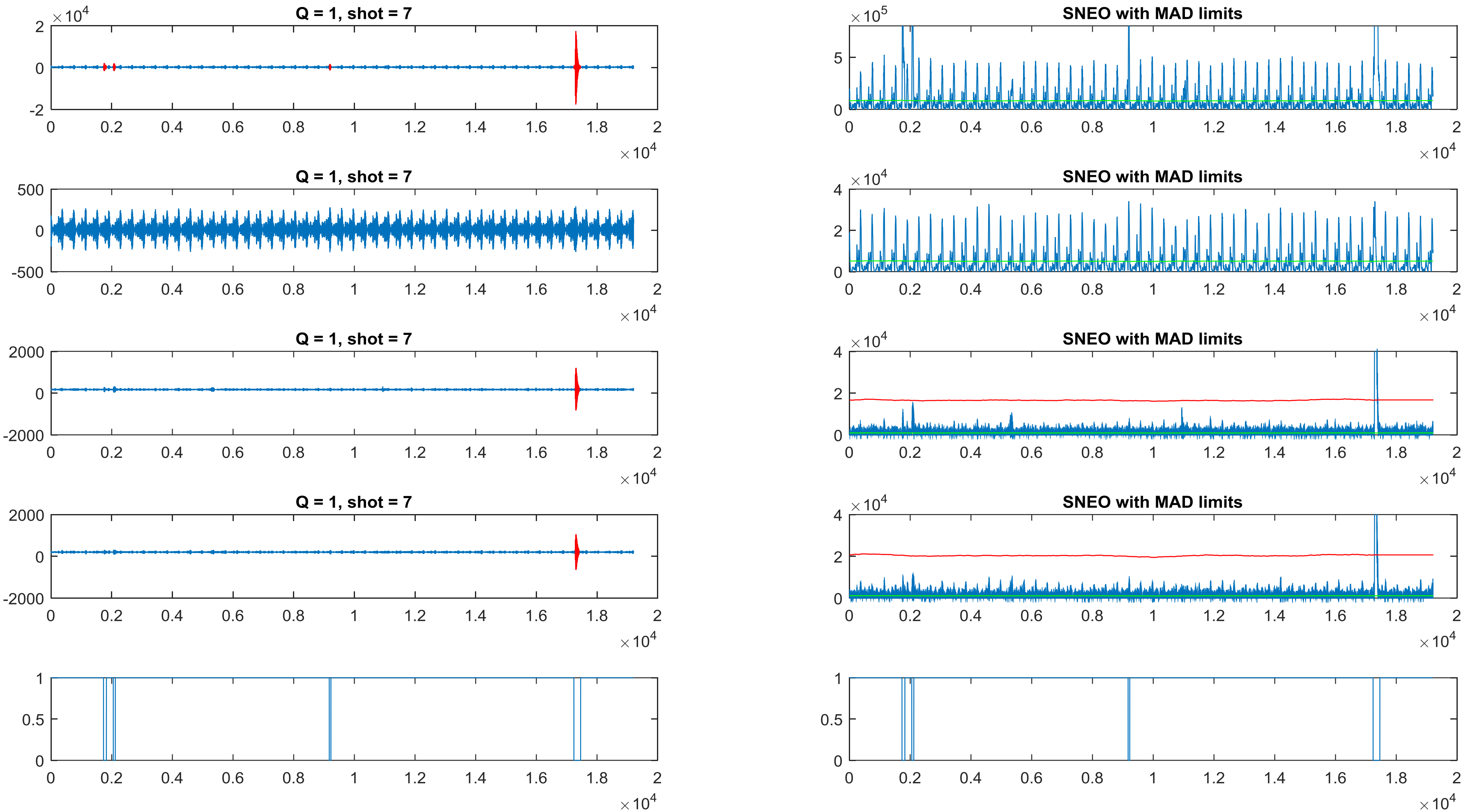


Median absolute deviation (MAD)

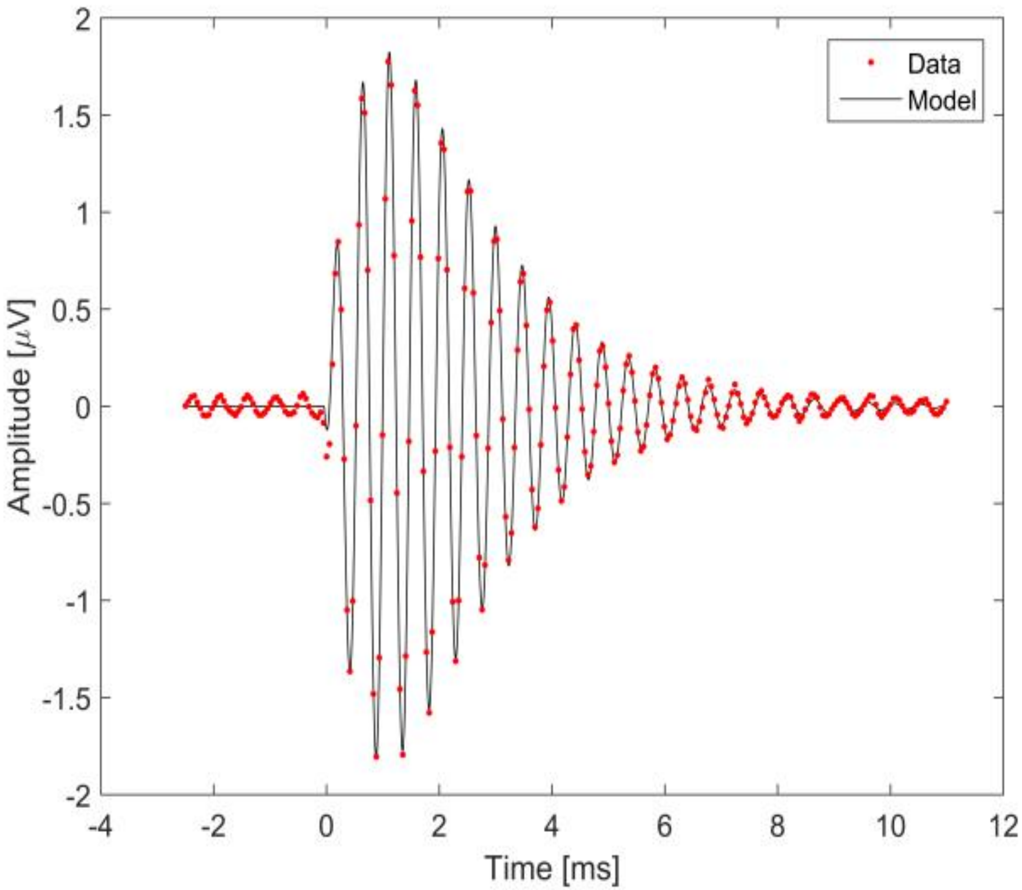
$$MAD = median_i\{|x_i - median_j\{x_j\}|\}$$

$$Threshold \propto MAD$$

Despiking – multichannel results



Modelbased despiking



B07 Despiking of magnetic resonance sounding signals

Jakob Juul Larsen (Aarhus University), Esben Auken (Aarhus University)

Subtraction of powerline harmonic noise

GEOPHYSICS, VOL. 58, NO. 6 (JUNE 1993), P. 898–903, 4 FIGS.

Subtraction of powerline harmonics from geophysical records

Karl E. Butler* and R. Don Russell*

INTRODUCTION

Harmonic noise generated by power lines and electric railways has plagued geophysicists for decades. The noise occurs as electric and magnetic fields at the fundamental frequency of power transmission (typically 60 Hz in North America) and its harmonics. It may be recorded directly during time-domain measurements of electric and magnetic felds, or indirectly, by geophone cables during the acquisition of seismic data.

Two processing techniques for suppressing stationary powerline noise in a time series are presented. Both techniques involve subtracting an estimate of the harmonic component. Unlike notch filters, they are capable of sup-

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Removal of power-line harmonics from proton magnetic resonance measurements

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Noise cancelling of MRS signals combining model-based removal of powerline harmonics and multichannel Wiener filtering

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Subtraction of powerline harmonic noise

- Recorded surface NMR signal decomposition

$$p(n) = NMR(n) + h(n) + w(n) + spikes(n)$$

random noise

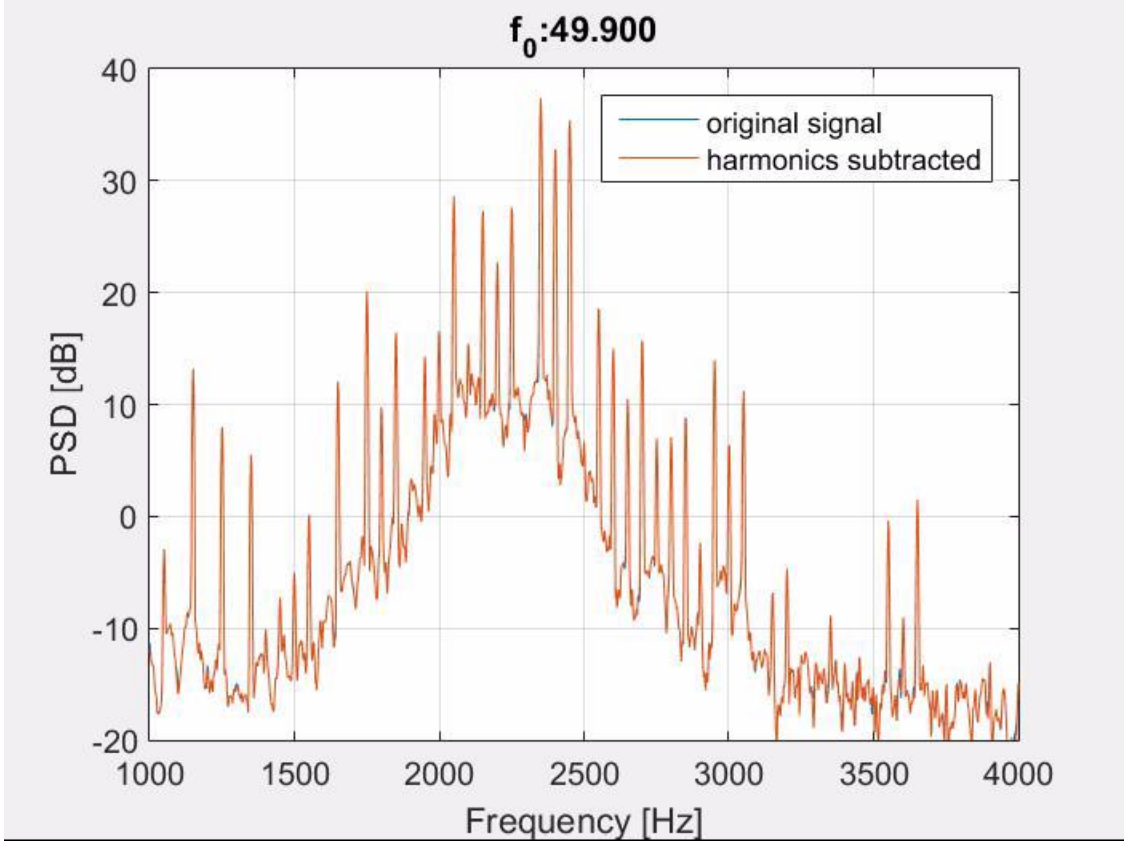
- Powerline harmonic noise model

$$h(n) = \sum_q A_q \cos(2\pi q f_0 n + \varphi_q) \qquad typically\ 10 \leq q \leq 80$$

$$= \sum_q \left(C_q \cos(2\pi q f_0 n) + D_q \sin(2\pi q f_0 n)\right)$$

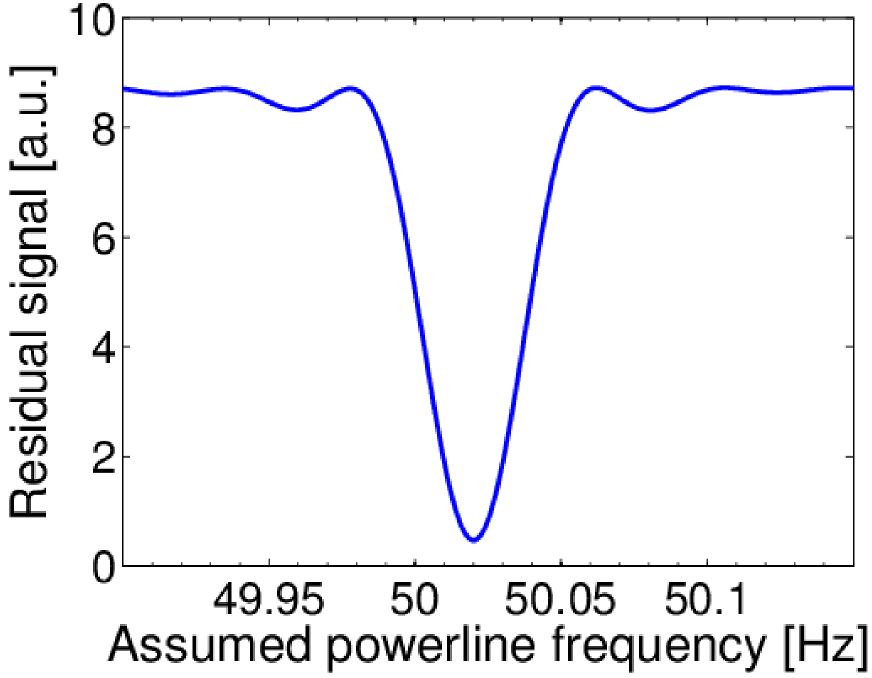
- Assumption: A_q, f_0 and φ_q are constant within one measurement

Subtraction of powerline harmonic noise



Data recorded in Odder, Denmark with a Numis Poly

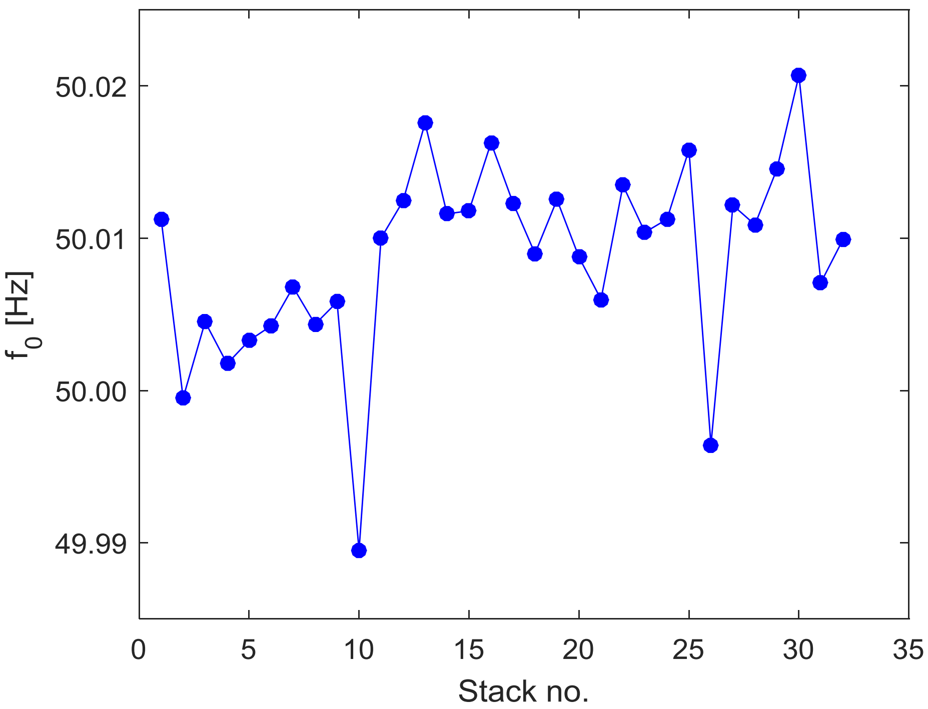
Subtraction of powerline harmonic noise

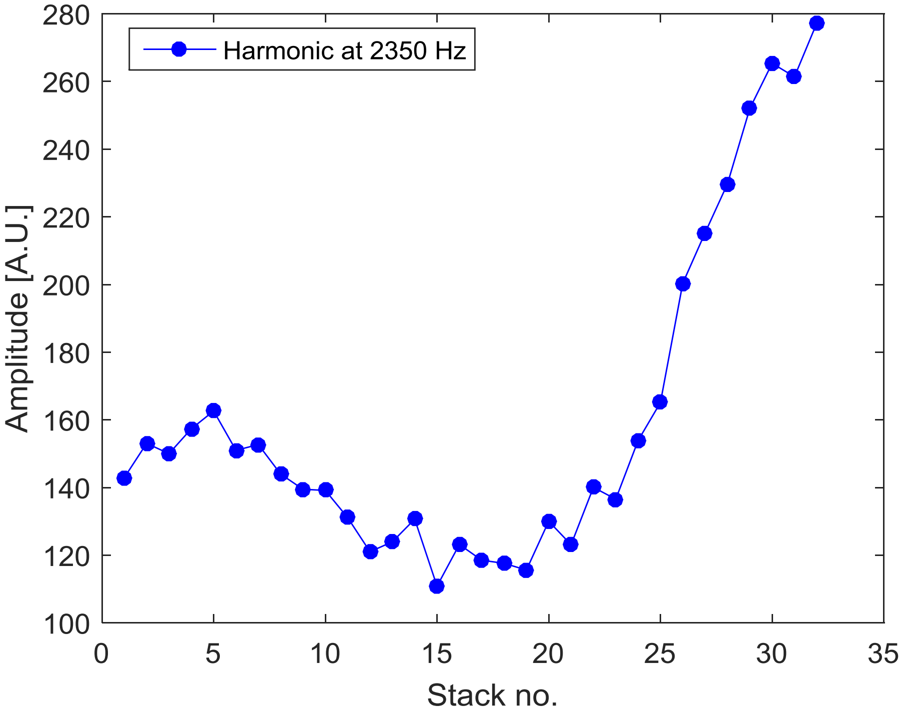


- Fundamental powerline frequency can be determined to within ~1 mHz

Data recorded in Odder, Denmark with a Numis Poly

Subtraction of powerline harmonic noise





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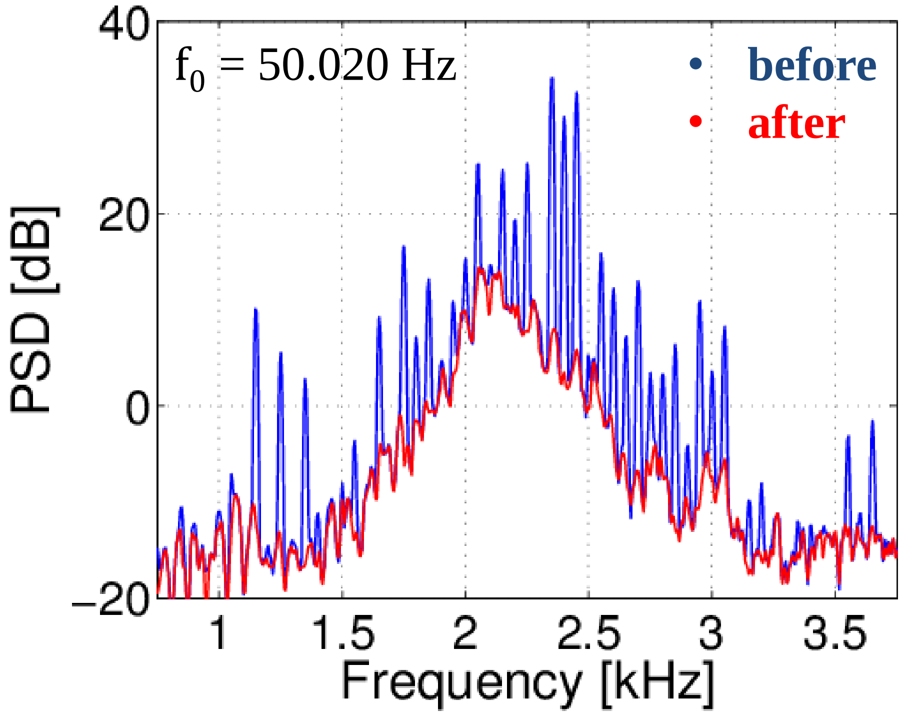
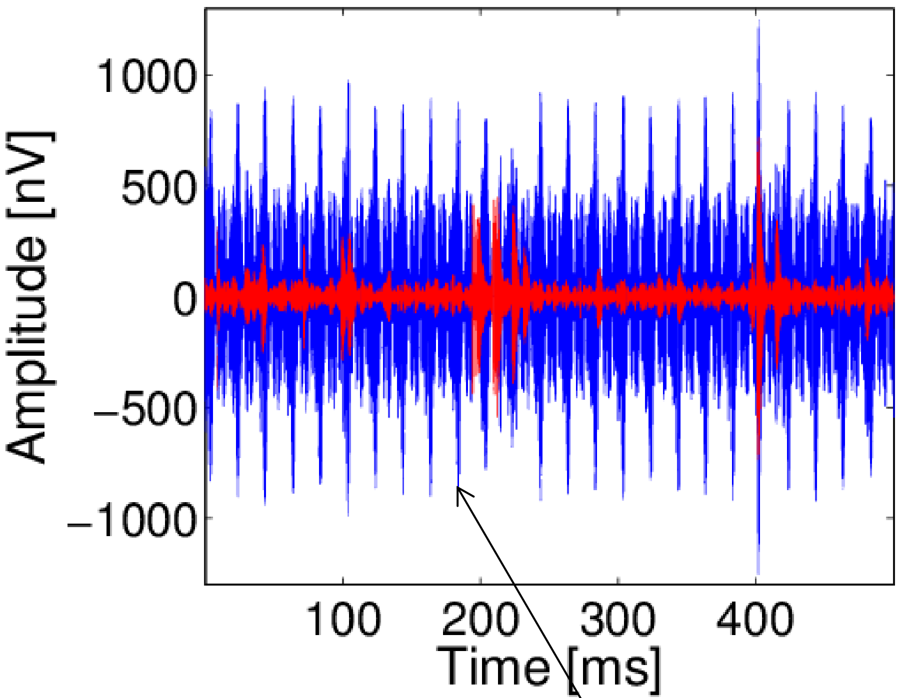
Subtraction of powerline harmonic noise





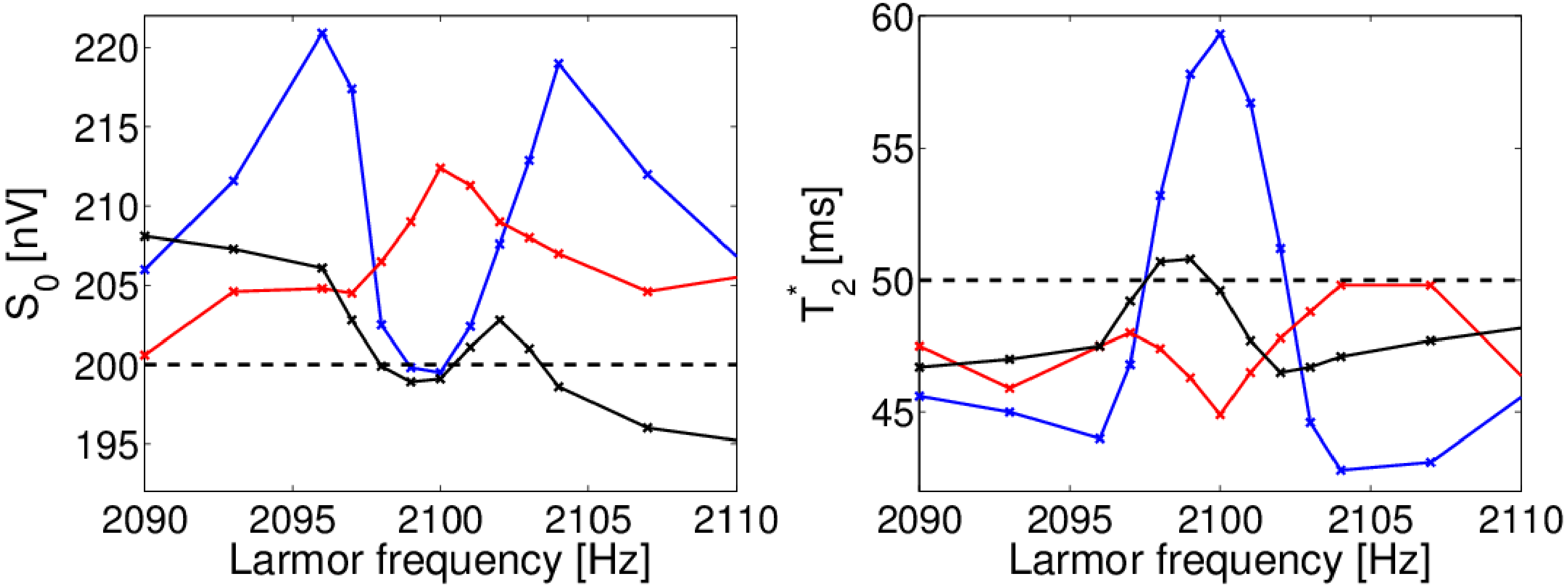
In this particular case, approximately 96% of the recorded energy resides in powerline harmonics

Small spikes are visible after powerline harmonics removal

What happens if the Larmor frequency is close to $m \times f_0$?

- Synthetic signal embedded in a real noise record, 32 stacks, 500 ms long

$$s(t) = s_0 \cos(2\pi f_l t + \phi)\, e^{-t/T_2^*} \qquad s_0 = 200\, nV,\ T_2^* = 50\, ms$$

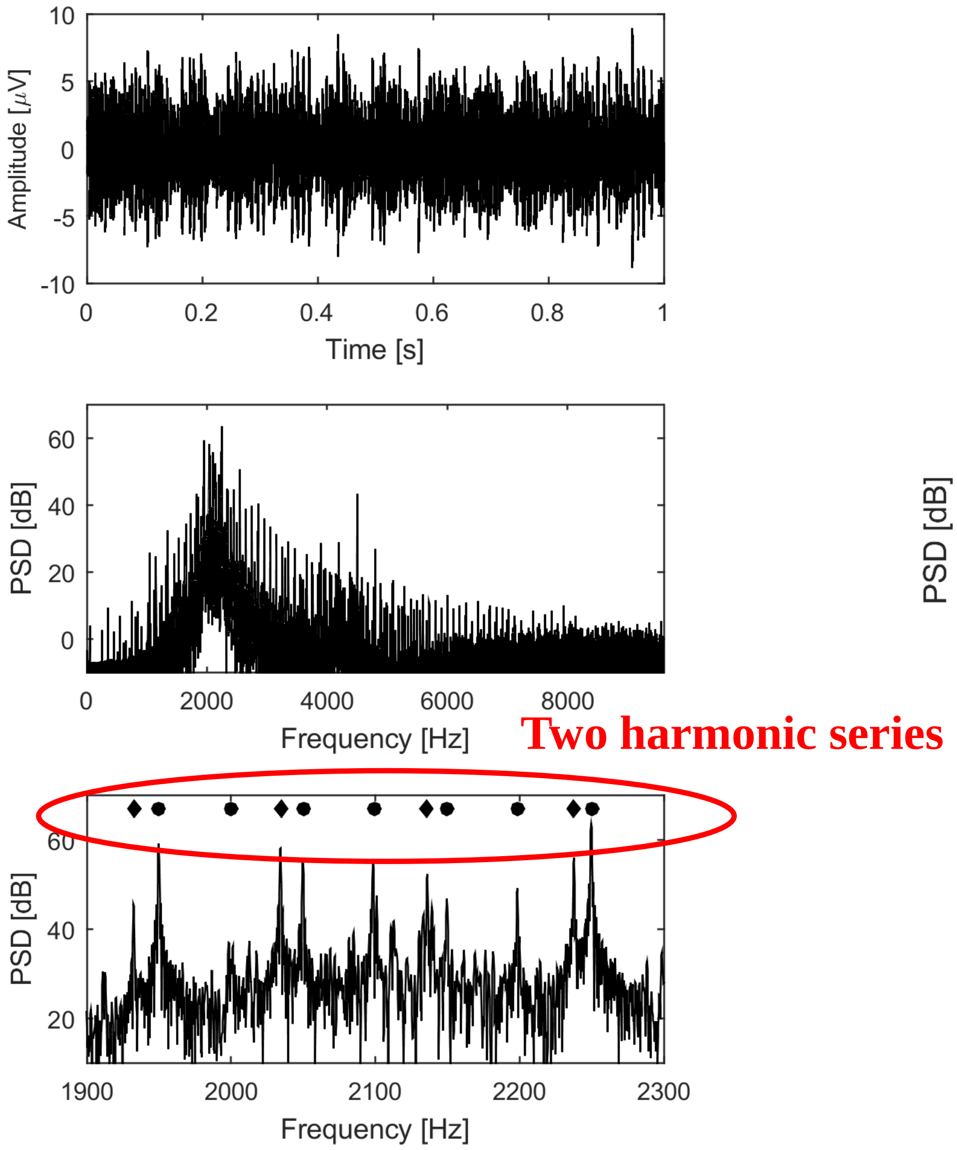


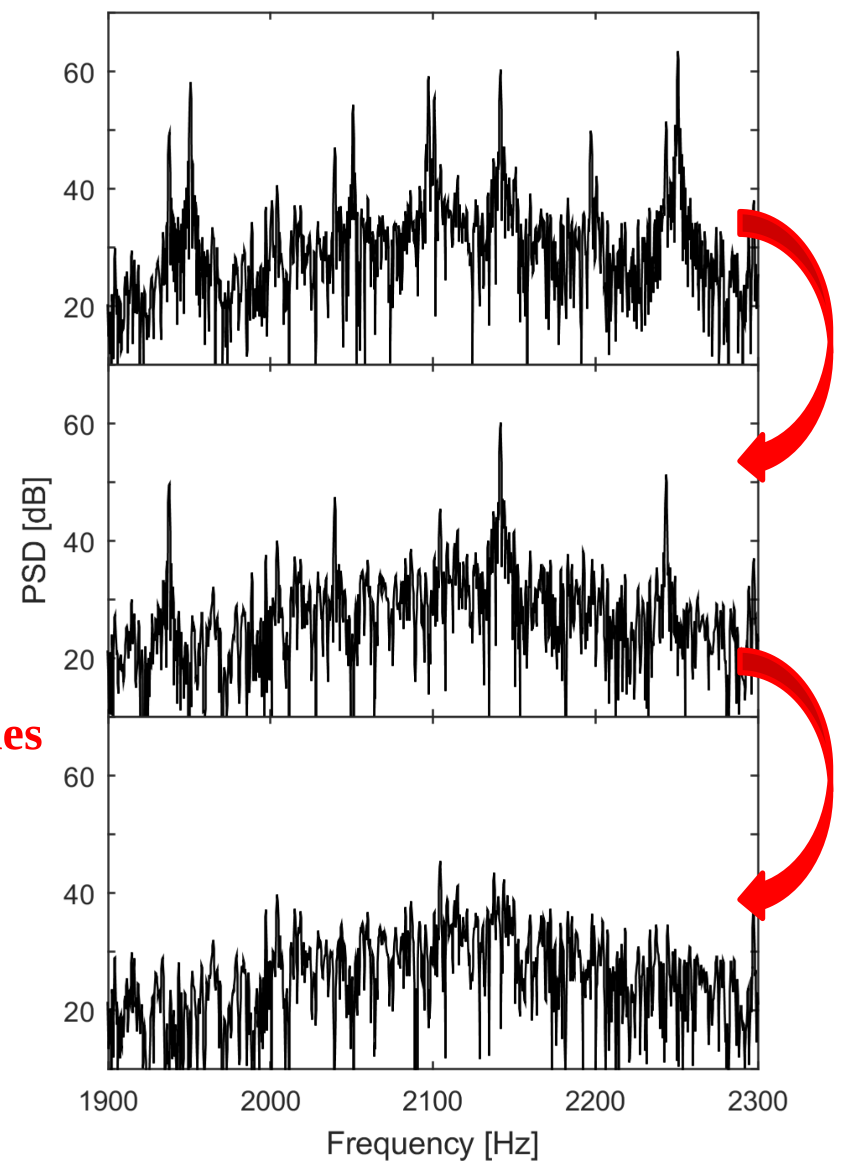
(1) Simple stacking, (2) Multichannel Wiener filter, (3) Model-based powerline removal

- Spikes blanked out in all experiments

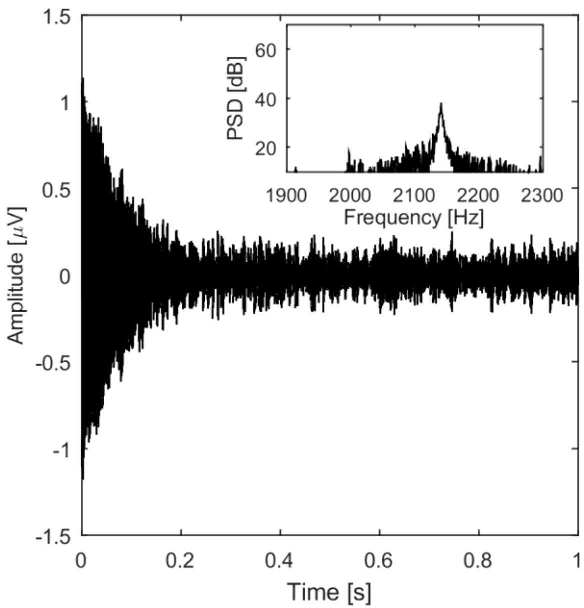
The model is fitted on last 250 ms and extrapolated

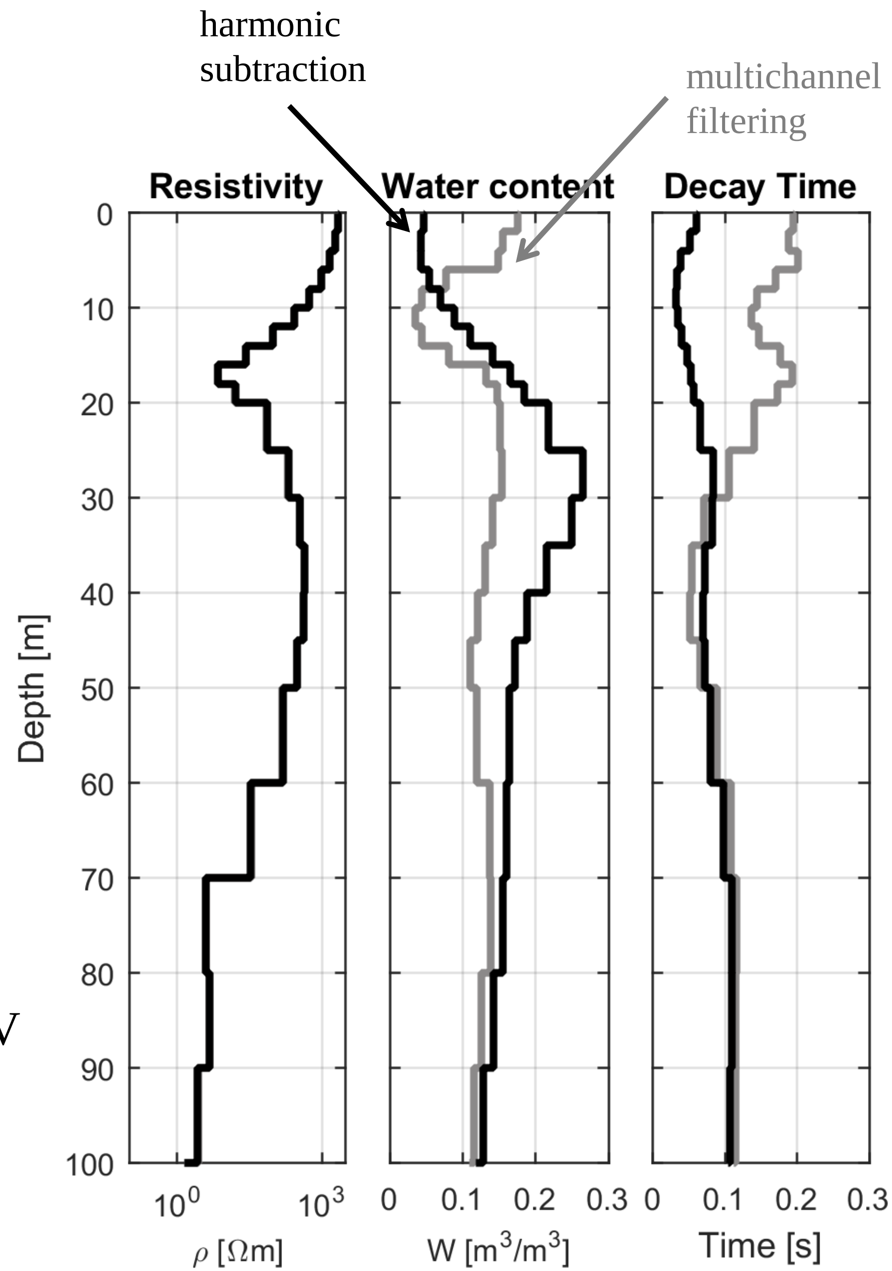
Example from Ristrup





Example from Ristrup

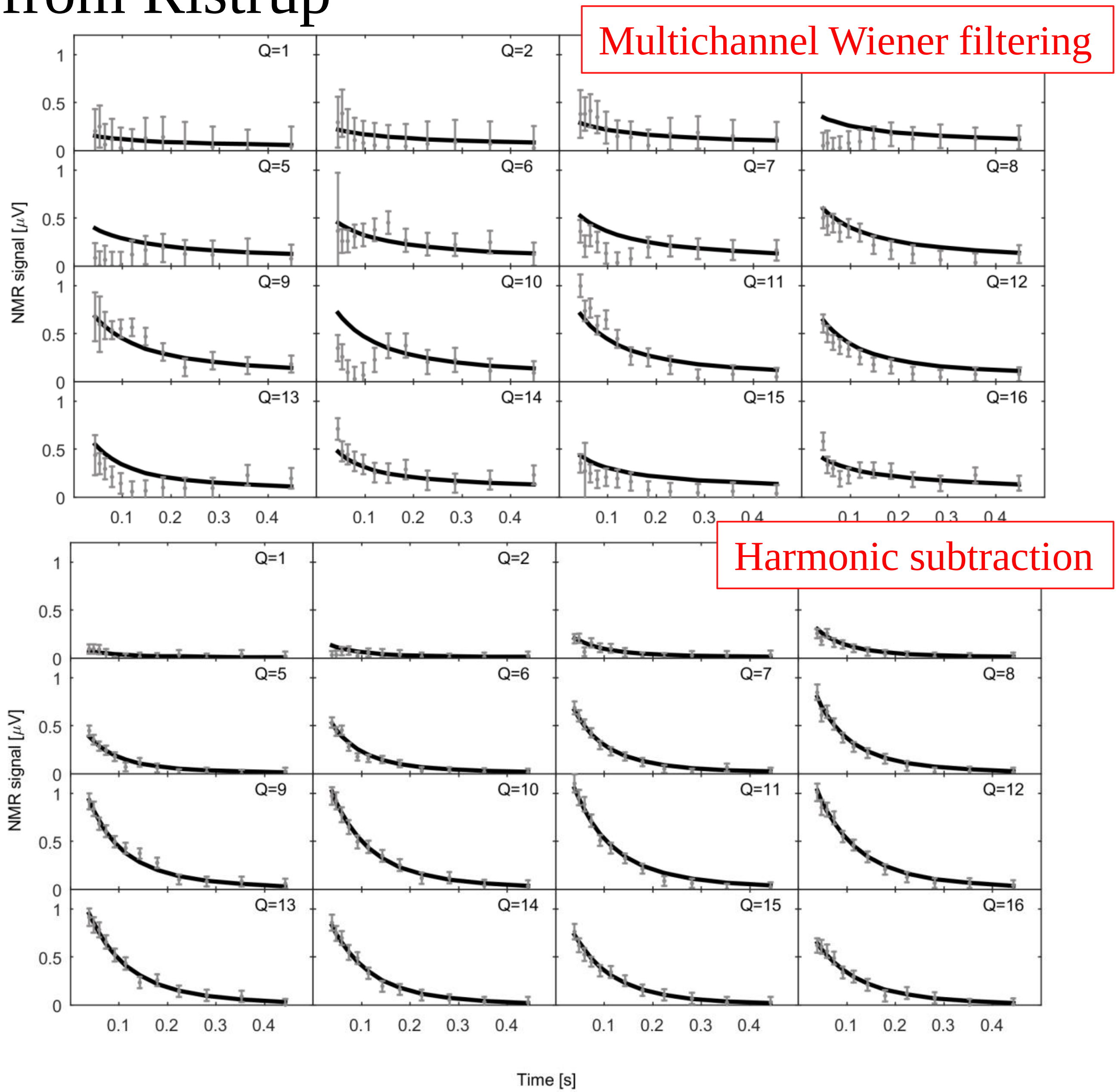




Final RMS values

Multichannel Wiener filtering: ~150 nV
Harmonic subtraction: ~ 60 nV

Example from Ristrup



Other approaches

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Joint application of a statistical optimization process and Empirical Mode Decomposition to Magnetic Resonance Sounding Noise Cancelation

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Statistical analysis

ABSTRACT

The signal quality of Magnetic Resonance Sounding (MRS) measurements is a crucial criterion. The accuracy of the estimation of the signal parameters (i.e. E_0 and T_2^*) strongly depends on amplitude and conditions of ambient electromagnetic interferences at the site of investigation. In this paper, in order to enhance the performance in the noisy environments, a two-step noise cancelation approach based on the Empirical Mode Decomposition (EMD) and a statistical method is proposed. In the first stage, the noisy signal is adaptively decomposed into intrinsic oscillatory components called intrinsic mode functions (IMFs) by means of the EMD algorithm. Afterwards based on an automatic procedure the noisy IMFs are detected, and then the partly de-noised signal is reconstructed through the no-noise IMFs. In the second stage, the signal obtained from the initial section enters an optimization process to cancel the remnant noise, and consequently, estimate the signal parameters. The strategy is tested on a synthetic MRS signal contaminated with Gaussian noise, spiky events and harmonic noise, and on real data. By applying successively the proposed steps, we can remove the noise from the signal to a high extent and the performance indexes, particularly signal to noise ratio, will increase significantly.

A04 Noise removal in MRS applications: field cases and filtering strategies

Jean-François Girard (BRGM), Sébastien Penz(BRGM), Aurore Texier (BRGM), Jean-Michel Baltassat (BRGM), Anatoly Legchenko (IRD, LTHE)

C06 Improving Parameter Estimation for Surface-NMR Data by Singular Spectrum Analysis Framework

Reza Ghanati (University of Tehran), Mohammad Kazem Hafiti (University of Tehran), Mahdi Fallasafari (University of Tehran)

E02 CEEMD-DFA and Variance Criterion Based De-noising Method Applied to Magnetic Resonance Sounding

Reza Ghanati (University of Tehran), Mohammad Kazem Hafiti (University of Tehran), Mahdi Fallasafari (University of Tehran)

F04 High-efficient MRS noise cancellation using independent component analysis

Tingting Lin (Jilin University), Siyuan Zhang (Jilin University), Ling Wan (Jilin University), Jun Lin (Jilin University)

Our ‘recipe’ for noise reduction

1. **Quality assurance**
2. **Spike identification**
3. **Harmonic subtraction**
4. **Second spike identification**
5. **Multichannel filtering, if applicable**
6. **Stacking of records**