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Noise Cancellation of Multichannel Magnetic Resonance Sounding Measurements with Wiener and Adaptive Filters

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SUMMARY

Magnetic resonance sounding (MRS) is a unique and promising hydrogeophysical technique. Due to its ability of providing a direct estimate of the water content and estimates of the porosity in the subsurface, MRS has the potential of being a great team player in the field of hydrological prospecting.

However, the MRS measurements suffer from a low signal to noise ratio due to the signal being inherently weak and the susceptibility to electromagnetic interference. The low signal to noise ratio currently impedes the applicability of the technique, particularly in urban areas. In recent years the development of multichannel MRS has opened up new possibilities for advanced noise cancellation methods. Before multichannel MRS can realize its full potential robust and reliable methods for noise cancellation must be developed.

In this work we compare two noise cancellation methods: The multichannel Wiener filter and a multichannel adaptive noise cancellation filter. The comparison is performed on noise records from a multichannel MRS instrument with or without synthetic signal added. Our results show that adaptive noise cancellation performs better than the Wiener filter for both pure noise removal and for recovery of the parameters of the synthetic signal.

Introduction

Mapping of groundwater resources is important for optimum managing, utilization and protection of this often scarce resource. Magnetic resonance sounding (MRS) is a technique that shows promising results for contributing to the field of hydrological investigations. Where other geophysical methods give an indirect measure through physical parameters, MRS allows for a direct measure of the water content through the amount of hydrogen protons, Legchenko and Valla (2002). Besides the water content MRS measurements allows for porosity, permeability, transmissivity and specific yield estimates, Legchenko et al. (2002).

The voltages measured in a typical MRS setup are in the nV to μV range and all measurements are heavily masked by electromagnetic interference from thunderstorms to electrical fences, railways and other forms of man-made noise. Due to the sensitivity to man-made noise the MRS technique is currently unsuitable for measurements in urban areas. For single-channel MRS soundings some of the most used noise filtering techniques are notch filtering, Legchenko and Valla (2003) and the use of a figure-8 loop geometry, Trushkin et al. (1994). These techniques have some drawbacks. With a notch filter the MRS signal may be distorted and with the figure-8 loop setup the sensitivity function becomes more complicated and the depth penetration is decreased. With the new multichannel MRS equipment which has become available in the recent years it is anticipated that the use of more sophisticated noise cancelling techniques can improve the efficiency of the method and it will be possible to get around the drawbacks from the single-channel MRS filtering techniques, Dluglosch et al. (2011). Best practice has still to be established in multichannel noise filtering. In particular it is necessary to find the optimum methods for signal processing and analysis. The ranges of applicability and constraints on these methods also needs to be determined.

In this work we report on our progress on optimizing the noise cancelling in multichannel MRS. We compare the two most often used methods of noise cancelling; The multichannel Wiener filter, Neyer (2010); Mueller-Petke and Yaramanci (2010) and a multichannel adaptive noise cancelling filter similar to that reported by Walsh (2008).

Method

The idea behind multichannel MRS is that a primary loop is used to first transmit the excitation signal and later record the MRS signal. A number of reference loops, 3 in this case, are placed around the primary loop but so far away that they do not measure the MRS signal but only the noise environment on the site. When the signals from the primary loop and the reference loops are recorded simultaneously the noise in the channels will be partly correlated. If the transfer functions between the reference loops and the primary loop are known and the correlation is high, the noise recorded in the reference loops can be filtered into a replica of the noise in the primary loop and subtracted from the primary signal to give an increased signal to noise ratio.

The transfer function can be explicitly estimated with a Wiener filter and explicitly used for the transformation of noise as shown in the upper part of Fig. 1 or it can be estimated and used less explicitly in an adaptive noise cancelling setup, bottom half of Fig. 1, Hayes (1996).

A synthetic signal is used for the *in silico* experiments so a comparison with the desired outcome is possible. The synthetic MRS signal is given by $s(t) = S_0 \cos(2\pi f_0 t + \phi)e^{-t/T_2^*}$ with noise added. To ensure as realistic conditions as possible, real noise data collected in august 2010 in Risby, Denmark with a NUMIS Poly (IRIS instruments) is used. It should be noted that this method is based on the assumption that the noise in a MRS measurement is purely additive to the MRS signal.

As shown in Fig. 1 the Wiener filter is determined by measuring simultaneous noise records of the primary and reference loops. Auto- and cross correlation functions are estimated from these data and
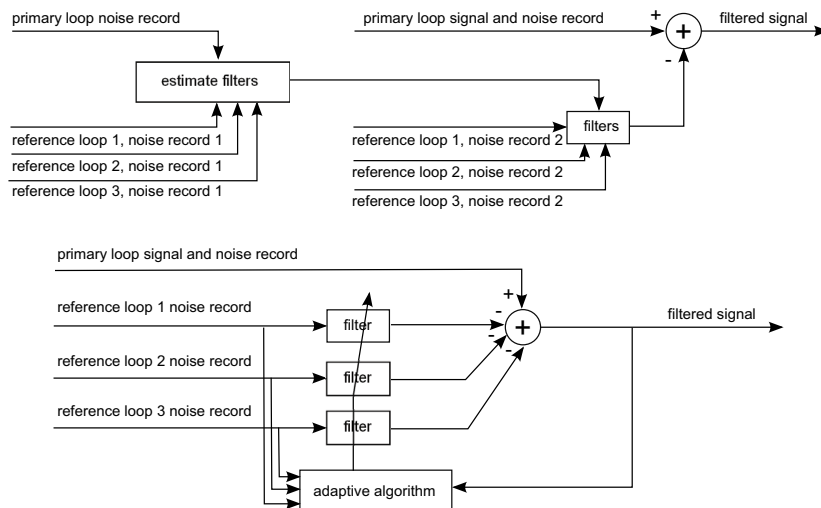
Figure 1 *Schematic drawings of the two noise cancelling setups. Top: Wiener filtering setup. Bottom: Adaptive noise cancelling setup.*
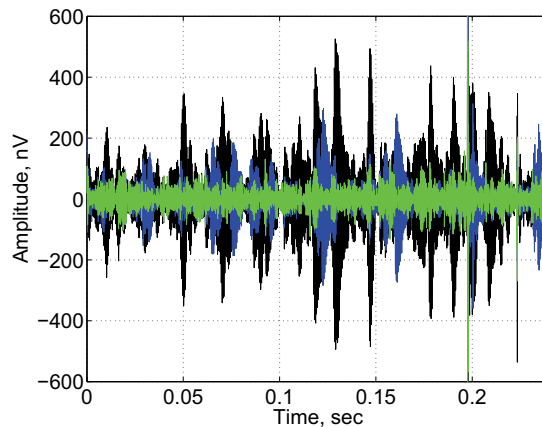

Figure 2 *Noise cancellation on noise-only measurements with pure stacking (black), Wiener filtering and stacking (blue) and adaptive filtering and stacking (green). 36 stacks are used in all three cases.*

used to calculate the transfer functions. The transfer functions are then used to filter the noise in the subsequent reference records and the output is subtracted from the primary loop when it measures both MRS signal and noise. The measurement of the transfer function is repeated before each new record, Neyer (2010).

In adaptive noise cancelling, bottom part of Fig. 1, an adaptive algorithm continuously adjusts filters on the reference loop signals and subtracts the outputs from the primary loop signal. The method can be used without the need for a silent measurement span to record noise. Instead the stacks can be recorded one after another while the adaptive filter continuously tracks any changes in the transfer functions. At start-up, a number of stacks must be used to train the adaptive filter. A stable adaptive algorithm is needed due to the fluctuating and spiky behavior of the noise signal. It is important that the adaptive algorithm is operated so slowly that it only cancels noise and leaves the signal undisturbed. The standard LMS algorithm is used in this work with a small step-size chosen to be 0.0003 of the maximum, Hayes (1996).

After filtering and stacking, estimates of S_0, f_0, ϕ and T_2^* are extracted with phase corrected digital quadrature detection and standard peak finding and fitting methods, Neyer (2010).

	Model	Pure stack	Wiener filter	Adaptive filter
S_0 [nV]	200	209$\pm$4	193$\pm$2	198$\pm$1
f_0 [Hz]	2137	2136.82$\pm$0.08	2136.91$\pm$0.08	2136.99$\pm$0.08
ϕ [rad]	2	2.15	2.03	1.99
T_2^* [ms]	200	207.3$\pm$8.4	230.4$\pm$5.3	196.3$\pm$2.3
MSE		11200	2790	841

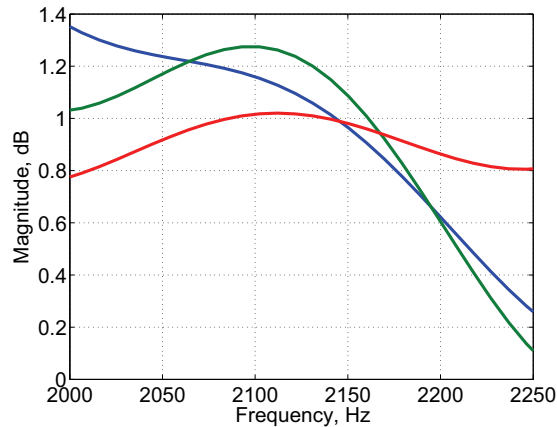*Table 1 Comparison of extracted parameters, see text for details.*

Figure 3 Frequency responses of three subsequent measurements of a specific transfer function.

Results

One of the key results of this work is shown in Fig. 2. The ability of the different algorithms to remove noise in the primary channel can be easily compared for measurements performed without any excitation signal. 36 measurements have been either purely stacked, Wiener filtered and stacked or adaptively filtered and stacked. The length of the Wiener filters are 50 taps per channel, Neyer (2010). For the adaptive filters 15 taps per channel is used. The figure shows time series for each of these scenarios. The graph shows that adaptive filtering outperforms Wiener filtering that again outperforms pure stacking. No attempt has been made at de-spiking the time series before stacking. The figure shows that all of the algorithms are affected by spikes.

The relative average power in the time series is a quantitative measure of the amount of noise cancellation. The ratios between the different methods are:

adaptive filtering	Wiener filter	pure stacking
1	2.3	8.9

Table 1 shows the retrieved signal parameters obtained with phase corrected digital quadrature detection and fitting on the signal for either a pure stacking of 36 measurements, with Wiener filtering and stacking or with adaptive noise cancelling and stacking. The results shows that adaptive noise cancelling shows better results than both pure stacking and Wiener filtering. The fitted parameters are closer to the model parameters and the standard deviations are lower. The bottom row shows the mean squared error between the data and the fitted model for each signal processing method. Again, the numbers support the conclusion that adaptive filtering is a better choice of noise cancellation.

In figure 3 the frequency response of the Wiener filter transfer function between a reference and the primary loop is shown for three subsequent stacks recorded with 1-2 seconds interval. The deviations between the curves shows that the measured transfer function is not constant. Given the very short time

between the measurements the major part of the deviations can be attributed to noise in the measurements of the transfer functions. This observation explains the superior behavior of the adaptive filter. Due to the slow convergence speed used in this work, the adaptive estimate of the transfer function is effectively averaged over a much longer time interval than for the Wiener filter. The adaptive filter will still track slowly varying changes as caused by e.g. thermal effects during the acquisition of data.

Conclusions

We have investigated two different methods for noise cancellation in multichannel MRS: multichannel Wiener filtering and multichannel adaptive noise cancellation. We find that the adaptive filtering approach outperforms the multichannel Wiener filter. The major reason for this improved noise cancellation is the noise averaging effect of a slowly adapting filter.

The parameters of a synthetic signal in a real noise record has been extracted with very high precision and confidence. This implies that a robust procedure for processing of MRS data is to optimize the filter settings on pure noise signals with a synthetic MRS signal added before these processing parameters are used on real data.

Further optimization of the use of adaptive algorithms in noise cancellation of MRS is possible, i.e. no attempt have currently been made to de-spike the records before processing.

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