

## Multichannel magnetic resonance sounding with wirelessly operated coils – A design study

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### SUMMARY

The invention of multichannel MRS instruments, where additional channels are used for reference measurements of noise has been successful in improving the signal to noise ratio of MRS measurements, but the signal to noise ratio is still inadequate for reliable measurements in many places of interest. To further improve on noise reduction, better methods for dealing with complex noise fields are needed. In available systems the reference channels are connected to a base station by wires. In this paper we argue that by using reference channels with wireless connections to the base station improvements in noise reduction can be expected. We present and discuss a design study of an MRS receiver system using wireless reference channels. The design is based on using as many standard components as possible e.g. GPS disciplined oscillators for time synchronization and WiFi for communication between units.

**Key words:** Multichannel MRS, noise reduction techniques, wireless sensors, geophysics instrumentation.

### INTRODUCTION

Today, state of the art MRS systems are multichannel systems where the NMR excitation of groundwater and the subsequent measurement of the NMR signal are done with a primary coil. Additional reference coils are used to measure the electromagnetic noise at a number of positions in the vicinity of the primary coil. The purpose of the reference coil measurements is to provide a synchronous estimate of the electromagnetic noise in the primary coil. When this estimate is subtracted from the primary coil measurement, the noise in the primary coil measurement is cancelled under optimum circumstances. In practice, the noise cancellation is rarely complete as the noise in the primary coil and the noise in the reference coils are only partially correlated in complex noise fields.

The multichannel MRS systems that are available from vendors today use wires to transmit noise measured in one or several reference coils to a main unit controlling the generator and the signal acquisition, Walsh (2008), Dlugosch et al. (2011). The use of wired reference coils is, however, unfortunate for several reasons.

First of all, the use of wires imposes limits on the distance between the primary coil and the reference coils. This often makes it difficult if not impossible to locate the reference coils in the vicinity of a particular noise source. The end effect of this is that the noise measured in a particular reference channel is typically a mixture of noise from several sources which deteriorates the noise reduction using standard techniques, e.g. multichannel Wiener filtering, see Larsen *et al.* (2013). By placing reference coils in the vicinity of particular noise sources much better separation of noise components can be achieved.

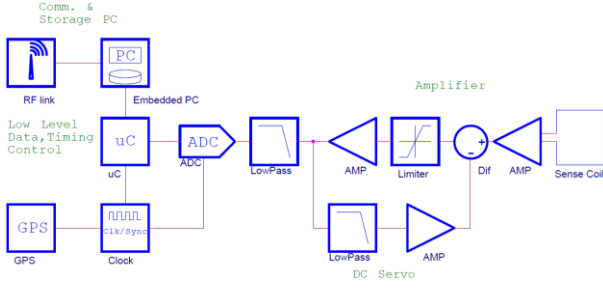
Second, in continuation of the above argumentation, the ability to have a larger separation between the primary coil and the reference coil reduces the risk of accidentally measuring a MRS signal in the reference coils. The presence of any such MRS signal in the reference coils will distort the multichannel signal processing and the end result are wrong estimates of the water content and the relaxation times.

Third, the use of wireless reference channels provide much more freedom in the placement of reference coils in field measurements. One example is if several soundings are to be carried out on a particular site, e.g. a line scan across a geologic feature, wireless reference channels will allow the field worker to save time as the reference coils need to be deployed only once and only the primary coil must be moved between soundings.

There is hence a need to investigate the feasibility of wirelessly operated reference channels. In this paper we present a study of the practical feasibility of such a system. It must be stressed that the proposed system has been designed with the goal of improving the data acquisition of noise in reference channels but the system can also be used for measuring MRS signals if desired.

### GENERAL DESIGN SPECIFICATIONS

Figure 1 shows a block diagram of a wireless reference coil unit. The coil used to measure noise is either a standard reference coil as used in current MRS systems e.g. the Numis Poly system employs 10 m x 10 m, 7 turn coils or it can be made from shielded cables to minimize capacitively coupled noise which is much more localized than the inductively coupled noise and hence uncorrelated between the different receivers.



**Figure 1. Receiver coil unit consisting of sensing coil, amplifier, analog-to-digital converter, control logic and wireless link.**

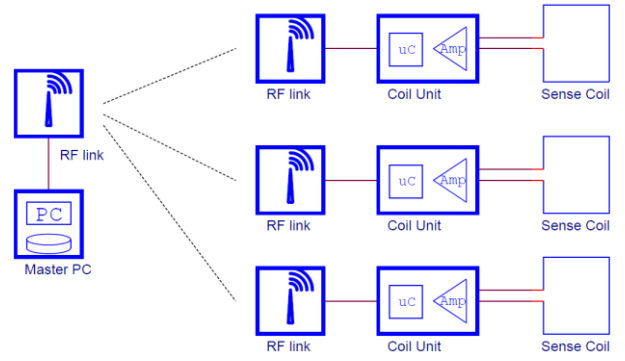
The signal from the coil is amplified by a low noise amplifier. The signal must pass through an anti-aliasing filter before it can be converted into the digital domain. The anti-aliasing filter can be implemented as a bandpass filter if e.g. only the noise in a frequency band around the Larmor frequency is desired. One consequence of a narrow bandpass filter is that impulsive noise is transformed into long spikes. If the anti-aliasing filter is instead implemented as a low-pass filter with a passband extending towards the Nyquist frequency, impulsive noise is less distorted, specifically, the duration of a spike retains short which can be beneficial for some spike removal algorithms. Furthermore a low frequency high-pass filter is desirable to remove 50/60 Hz hum. For this purpose a DC servo amplifier is added, which enables both auto-zeroing the DC offset of the high gain amplifier and a DC coupled amplifier design. The latter is advantageous with regard to impulsive noise.

A second design issue is the dynamic range of the receiver system. When a reference coil is placed in the vicinity of a particular noise source, e.g. an animal fence emitting spikes, the signals from this source can become very big compared to noise from other sources and the dynamic range of the receivers must be designed with this disparity in amplitude of different noise sources in mind as discussed below.

In the proposed system a microcontroller controls the data acquisition. The main tasks of the microcontroller are communication with the embedded PC, synchronization and time stamping of the data stream. During acquisition the recorded data are stored in on-board memory. The recorded data are subsequently transferred to a PC for long term back-up storage and transfer to the main unit.

The reference coil units are controlled by a main unit through a WiFi network, figure 2. The recorded data are continuously transferred from the reference coil units to the main unit using a network-attached storage (NAS) approach employing off-the-shelf components. This approach has been successfully applied in other geophysical measurement systems. When the distance between the main unit and one or more reference units exceeds the WiFi operational range, repeaters can be utilized to extend the range.

The continuous transfer of data to the main unit allows the operator to monitor the quality of data as they are acquired. The available data can be used to carry out real-time analysis of the noise reduction efficiency and the progress of measuring the MRS signal.



**Figure 2. System overview. A master unit and three coil units are connected by a wireless network.**

## TIMING CONSIDERATIONS

An important issue in the design of a multichannel MRS system with wirelessly operated reference coils is to ensure that the signals in the primary coil and the reference coils are synchronously sampled. All channels must be sampled with exactly the same sampling frequency and any timing jitter in the sample-start clocks for channels must be kept below a small fraction of the sampling period. The reason for these design constraints is the fact that the noise in the primary coil and the reference coils are not exactly identical due to the receiver's different geographical positions, tilt and orientation in the landscape and small difference in the electronic components. Therefore transfer functions have to be applied to the noise recorded with the reference coils before it can be subtracted from the noise in the primary coil. The transfer functions are constant from shot to shot if all channels are sampled with the same sampling frequency and if there is no jitter in the sample-start clock. In this case good estimates of the transfer function can be gathered by averaging over many shots and a good noise cancellation can be obtained. If the sampling frequency is not constant or if there is jitter in the sample-start clocks the transfer functions must be estimated from shot to shot. Inevitably the quality of the transfer function estimate is poorer and as a consequence the noise cancellation is reduced.

As an example of this problem a simple estimate of the influence of a sample-start jitter can be obtained as follows. Consider the case where a primary coil and a reference coil are both disturbed by a harmonic noise source at  $f_h=2.1$  kHz. The two coils are sampled at the same frequency,  $f_s=19.2$  kHz but the sample start of the reference coil is affected by jitter denoted by  $\phi$ . The effect of sample-start jitter is a phase shift of the reference coil signal. For simplicity the noise in both coils is assumed to have unit amplitude and zero phase. The noise in the two channels is given by the following expressions

$$N_p(k) = \cos\left(2\pi \frac{f_h}{f_s} k\right)$$

$$N_r(k) = \cos\left(2\pi \frac{f_h}{f_s} (k + \phi)\right)$$

For the jitter-free case,  $\phi=0$ . In this situation the optimum transfer function is  $H=1$  which would lead to complete noise cancellation.

$$N(k)|_{\phi=0} = N_p(k) - 1 * N_r(k) = 0$$

Table 1 shows the results of a calculation of the reduction in noise cancellation when the  $H=1$  transfer function is applied to a reference channel affected by sample-start clock jitter.

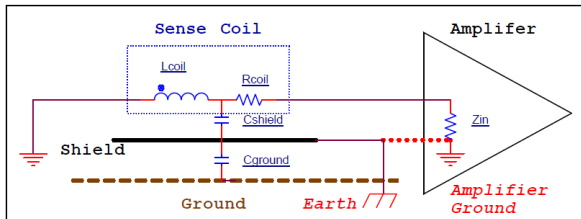
**Table 1. Noise reduction in the presence of sample-start jitter.**

$\phi$ [samples]	Noise [% of original]
0	0.0
0.01	0.7
0.1	6.9
1	67.4

From these results it can be concluded that sample start jitter should be as small as possible. E.g. to have less than 1% noise remaining the jitter must be less than approximately 1% of the sampling period to achieve good performance. For a sample frequency of 19.2 kHz this corresponds to a jitter of less than 0.5  $\mu$ s. This constraint on the maximum tolerable jitter and similar constraints on the clock frequency stability are easily met by modern timing systems using GPS-disciplined oscillators (GPS-DO). GPS-DO systems are available from many vendors and typically provide a very stable 10 MHz clock signal which can be used to control the timing of the microcontroller as well as a 1 PPS (pulse per second) output with an accuracy of less than 50 ns which can be used as sample-start clock.

Synchronization of the sample-start clocks between units is achieved due to the following procedure: the master unit sends a time stamp to the coil units indicating the planned start time ahead of the actual measurement. The coil units start sampling, when the time has elapsed according to the GPS receivers. Sample synchronicity is maintained by deriving the ADC clock from the GPS-DO. Thereby all units are ensured to sample synchronously with an uncertainty only determined by the GPS clock resolution.

### AMPLIFIER CONSIDERATIONS



**Figure 3. Equivalent circuit of sense coil and amplifier with an optional shield.**

Figure 3 shows the equivalent circuit of the sense coil and amplifier. Even for large coils the wavelength of MRS signals is much larger than the coil dimension. Thus modelling the sense coil as a lumped, first order system, the impedance of the sense coil is then given by the coil's self-inductance and the conductor's resistance. The coil's impedance together with the amplifier's input impedance  $Z_{in}$ , which is mainly resistive, forms a low-pass filter. If this low-pass filter's cut-off frequency lies within the frequency band of interest, the transfer function will depend on the shape, size and conductor cross-section of the coil, which obviously should be avoided. In order to accomplish this, the amplifier's input impedance must be as high as possible, which is easiest achieved by a single-ended amplifier topology.

If a balanced input amplifier was used, the typical resistive balancing circuit would have to be of very low resistance in order not to compromise the signal-to-noise ratio. As an example, an input resistance of only 10  $\Omega$  creates a thermal noise voltage density of 0.4  $nV/\sqrt{Hz}$ . However, the self-inductance of a single turn circular coil with a circumference between 40 and 400 m lies in the order of 0.1 to 1 mH (Grover, 2009) and a resistance between 0.5 and 5  $\Omega$  (1,5 mm<sup>2</sup>, copper conductor). With an assumed input resistance of a balanced amplifier of 10  $\Omega$ , this generates a low-pass filter with -6 dB points between 3 and 30 kHz. In the case of multi-turn coils the attenuation would be even more severe as inductance increases with the square of the number of turns. Thus the transfer function would be dependent on the coil configuration and is thus a less attractive solution.

The wireless system allows the amplifier to be placed directly at the sensor coil. The absence of connection cables makes a single-ended amplifier with high input resistance feasible, and results consequently in a cut-off frequency high enough to allow for a flat transfer function in the band of interest, which is the same for all units and independent of the used coil configuration.

Above, second order effects in the sensing coil due to capacitive coupling to ground are ignored, because both the site dependency is very hard to model in a general way, and capacitive effects are assumed not to be dominant. The latter is mainly based on the fact that the high series resistance of a measurement system, which is floating with respect to ground, will highly dampen any pole caused by the coupling capacity.

The purpose of the shield in figure 3 is to reduce noise generated by electric fields coupling capacitively to the sense coil. The shield basically short-circuits induced voltages to Earth (a ground electrode). The optional connection between amplifier ground and Earth can be added to suppress common mode noise, i.e. noise coupled both into shield and the sense coil. This is regarded optional, because the capacitance between the shield and sense coil, can then cause resonant peaking in the frequency response of the sense coil. However, even with a shield capacity per unit length of 100 pF/m and a 400 m long coil, the resonant peak will lie higher than 30 kHz, which is outside the frequency band of interest.

### NOISE AND DYNAMIC RANGE

MRS measurements require a high dynamic range and a very high signal-to-noise ratio. The signal chain for reference coil measurements should have the same resolution as the primary coil in order to have the same quantization error and resolution. Precision 24-bit analog-to-digital converters (ADC) with more than 18 effective, i.e. noise-free, bits are available, e.g. Texas Instrument's ADS1271, allowing for a noise free measurement range of about 110 dB.

Due to the single-ended amplifier topology, paralleling of input amplifier stages can easily be done, further reducing uncorrelated amplifier noise by a factor of  $\sqrt{N}$ , where  $N$  is the number of paralleled amplifiers. SPICE simulations of the proposed amplifier design show input-referred Johnson noise voltage densities below 1  $nV/\sqrt{Hz}$ . Hence, it is realistic to adjust the amplifier gain to map 10 nV to the 18<sup>th</sup> bit of the ADC, producing a noise free measurement range from 10  $nV_{pp}$  to 2.6  $mV_{pp}$ .

In extreme cases where this large dynamic range is insufficient, a dual gain scheme can increase the dynamic range of the receiver system. In a dual gain scheme the signal from the coil is sent to two amplifiers with low and high gain configurations respectively. During periods of low noise the signal from the high gain amplifier is efficiently sampled by the ADC using a large fraction of the available dynamic range. During periods of high noise as occurs during a spike, the signal from the high gain amplifier is saturated and hence unusable but the signal from the low gain amplifier is unsaturated. By fusion of the data from the two ADC's the dynamic range is effectively increased. Due to the high input impedance of the amplifier design it is straightforward to connect two or more amplifiers with different gain settings to the same coil.

## FILTERING

The proposed high resolution of the amplifier ADC chain requires a corresponding well designed anti-alias filter. Noise sources in the field cannot be assumed to naturally roll off towards higher frequencies in the pass-band. Thus the anti-alias filter has to achieve the same attenuation as the ADC resolution, if the noise free measurement range shall not be compromised by aliased frequency components, thus it has to achieve an attenuation of about 120 dB. The anti-alias low-pass filter has to be implemented in the analog domain. In consequence the proposed system will have a high sampling frequency in the order of 100 kHz so as to keep the filter design feasible. Although requiring a significant amount of digital bandwidth, contemporary WiFi networks and storage devices can easily deal with it.

An advantage of the high bandwidth is the rather undistorted processing of impulsive noise, originating e.g. from electric fences. Hum removal requires a high pass filter with a cut-off frequency around 200 Hz. A drawback of a high-pass filter in a signal path is the base line shift of the amplifier output due to exponential decay when excited by low frequency pulses with fast rise-/fall-time. Therefore we propose a DC coupled amplifier, where low frequency cut-off is realized by a servo circuit, which keeps the amplifiers offset at zero, which also acts as a high pass filter for periodic signals, i.e. 50/60 Hz hum, but is less prone to base line shift caused by pulses.

## CONCLUSIONS

This paper has described the main requirements for a multichannel MRS system employing wireless reference channels. The components needed for an implementation of such a system is readily available. In the above discussions the receiver units have been described as used for reference measurements of noise. We would like to stress that the same wireless units can also be used for measuring MRS signals. As an example the availability of easy deployable wireless receivers will be beneficial for 2D and 3D measurements.

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## REFERENCES

- Dlugosch, R., Mueller-Petke, M., Günther, T., Costabel, S. and Yaramanchi, U., 2011, Assessment of the potential of a new generation of surface nuclear magnetic resonance instruments. *Near Surface Geophysics*, 9, 89-102.
- Grover, F. W., "Inductance Calculations", Dover Publications, 2009 (reprint).
- Larsen, J. J., Dalgaard, E. and Auken E., 2013, Noise cancelling of MRS signals combining model-based removal of powerline harmonics and multichannel Wiener filtering. *Geophysical Journal International*, 196(2), 828-836.
- Walsh, D.O., 2008 Multi-channel surface NMR instrumentation and software for 1D/2D groundwater investigations. *Journal of Applied Geophysics*, 66, 140-150.