

# Low noise, multichannel surface NMR receiver system with wireless connections to receiver coils

**Lichao Liu**

Hydrogeophysics Group  
Department of Geoscience  
Aarhus University  
C. F. Møllers Alle 4  
8000 Aarhus C  
Denmark  
[Lichao.Liu@geo.au.dk](mailto:Lichao.Liu@geo.au.dk)

**Denys Grombacher**

Hydrogeophysics Group  
Department of Geoscience  
Aarhus University  
C. F. Møllers Alle 4  
8000 Aarhus C  
Denmark  
[Denys.Grombacher@geo.au.dk](mailto:Denys.Grombacher@geo.au.dk)

**Esben Auken**

Hydrogeophysics Group  
Department of Geoscience  
Aarhus University  
C. F. Møllers Alle 4  
8000 Aarhus C  
Denmark  
[Esben.Auken@geo.au.dk](mailto:Esben.Auken@geo.au.dk)

**Jakob Juul Larsen\***

Department of Engineering  
Aarhus University  
Finlandsgade 22  
8200 Aarhus N  
Denmark  
[jjl@eng.au.dk](mailto:jjl@eng.au.dk)

## SUMMARY

Surface NMR is a unique tool in groundwater geophysics due to its ability to directly measure the depth-resolved water content in the near sub-surface and provide depth-resolved estimates of the hydrological properties. The method is still in its infancy and several challenges must be overcome for the method to be generally applicable. These challenges include a low signal to noise ratio limiting measurements in many places of interest, a low production rate making the method costly in field campaigns and expensive instruments. We present a new multichannel, low noise surface NMR receiver system where receiver coils are connected to a main unit with wireless connections. The system works as a completely independent add-on to existing surface NMR transmitter systems. The receiver system are built as individual operated data acquisition boxes with timing synchronized by GPS and connected through WiFi to the main unit. The wireless feature allows for placement of reference receiver coils without any restriction imposed by cable lengths. The internal noise of the system operated in differential mode is  $1.8 \text{ nV}/\sqrt{\text{Hz}}$  measured on a single stack. We verify the performance of the system by measurements of a controlled source and by comparing our measurements with measurements performed with a commercial surface NMR system.

**Key words:** surface NMR, instrumentation, groundwater measurement, multichannel signal processing.

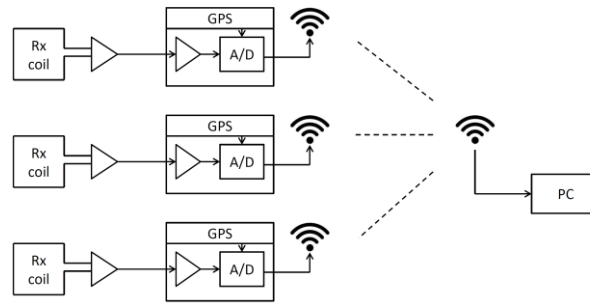
## INTRODUCTION

In a world, heavily relying on groundwater, there is a great need for tools that can help manage this resource. One such tool is surface nuclear magnetic resonance (NMR) which is a geophysical method for non-invasive measurements of groundwater down to a depth of ~100 m (Behroozmand *et al.*, 2015). The method is unique among the geophysical techniques as it is directly sensitive to the hydrogen nuclei in water molecules. The amplitude of the recorded signal is directly proportional to the water content in the sub-surface. The relaxation rate is controlled by the pore space environment where the water molecules reside and hence provide information on the hydrological properties of the sub-surface. Since the invention in 1987 (Semenov, 1987) surface NMR methodology has advanced significantly and the method has been tested or applied in a number of different contexts (Alaska, Egypt). Nevertheless, the method is still not as widespread as one could anticipate. There are several reasons for this. Recorded surface NMR data typically suffers from a poor signal to noise ratio, especially in data sets recorded in urban areas. In many cases of interests, surface NMR measurements are prohibited by high noise levels. The equipment is costly and the production rate is low, in many cases an entire day can be spent acquiring a single sounding.

Two types of surface NMR instruments are available today. The first type is single channel instrument systems where one coil is used to transmit the NMR excitation pulse. Subsequently, the coil is electronically rewired to act as a receiver recording the NMR decay (Semenov, 1987). In the second type of instruments, one primary coil is still used to transmit the NMR excitation pulse and record the NMR decay but the instruments also feature additional receiver channels. These extra receiver channels are used to record noise signals in remote reference coils (Radic, 2006; Walsh, 2008; Dlugosch *et al.*, 2011). Through signal processing the noise records are turned into a replica of the noise in the primary coil and subtracted from the primary coil data to give an NMR signal with a greatly improved signal to noise ratio. The multichannel instruments has also opened up for a shift in surface NMR methodology by using different coils to transmit the NMR excitation pulse and record the NMR decay. This has been used to perform 2D tomographic surveys (Jiang *et al.*, 2015). It also opens up for reduced dead time instruments, for using small receiver coils optimized for low noise signal detection and for easy field handling and optimized resolution (Behroozmand *et al.* 2016).

In this paper we present a new multichannel, low noise surface NMR receiver system with wireless connections to receiver coils. The receiver system operates independently on top of an existing surface NMR transmitter. The system has been developed in a modular fashion; it consists of data acquisition boxes, each with three channels. Each box is equipped with a GPS controlling the timing of the acquisition and a WiFi connection to a main unit as shown in Figure 1. The use of wireless connections brings a number of advantages to a surface NMR system. When noise reduction is performed with remote reference coils, the reference coils can be placed near identified noise sources, which can improve the multichannel filtering (Larsen, 2014). The reference coils can be placed further away

from the primary coil, which will reduce the risk on contamination of the reference coil data with NMR signal (Larsen and Behroozmand, 2016). Wireless connections will also increase survey speed as the remote reference coils can remain stationary and only the primary coil is moved between soundings.



**Figure 1: Schematic overview of the surface NMR receiver system. Three receiver coils are each connected to a data acquisition box with GPS controlled timing. Data from the three receivers are transferred to a main unit through WiFi connections.**

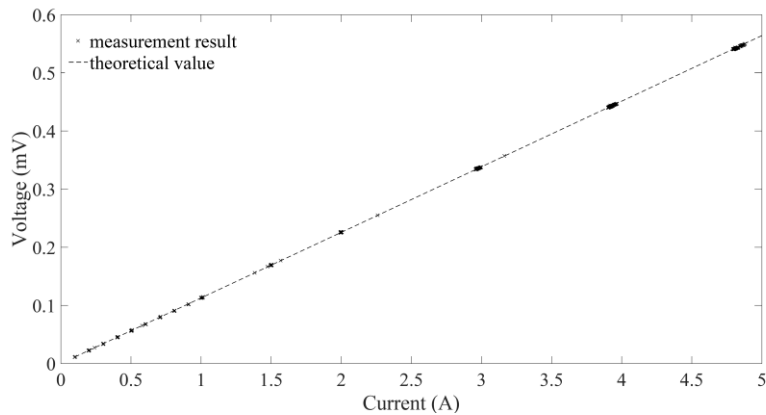
## RESULTS

Each data acquisition box features three independent channels each with a pre-amplifier attached directly at the coil and a second dual gain scheme and 24-bit AD converter sampled at 31.250 kHz within the box, Figure 2 (left). A GPS disciplined oscillator in each box controls the timing of the data acquisition. The timing jitter between receiver boxes is less than 100 ns, a value low enough to ensure the efficiency of multichannel filtering (Bahner *et al.*, 2015). The noise level of the system with shorted input is 1.8 nV/sqrt(Hz) measured on a single 1 s record. The electronics is controlled by a board with a dual core ARM processing unit and a programmable logic layer (FPGA). One of the ARM cores interfaces to a TCP/IP WiFi unit and handles all communication with a main unit and transfer of data. The main unit consist of a PC with a WiFi interface. To achieve full 360° coverage over long distances of several hundreds of meters, eight individual WiFi antennas are mounted on a mast, Figure 2 (right).

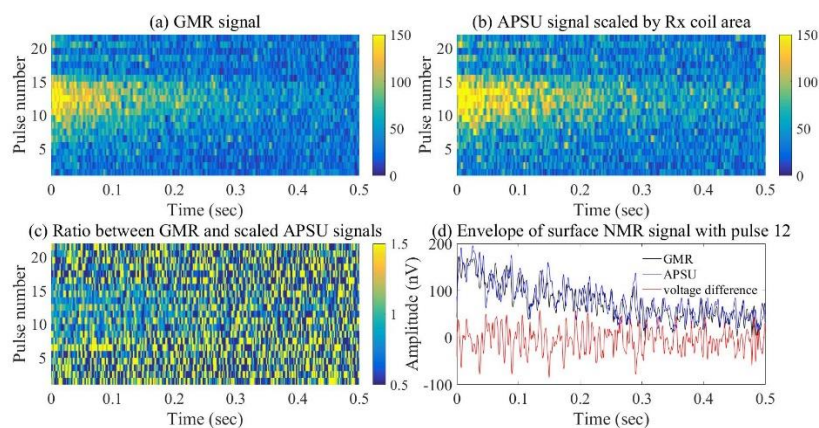


**Figure 2: Photos of the surface NMR receiver system. Left: A 3-channel receiver box powered by battery at the top left. The round dark gray unit at the top right is the GPS antenna. Right: The mast with the WiFi antennas. To obtain full 360° coverage 8 individual antennas are used. A receiver box is seen at the left side of the photo.**

We validate the performance of the receiver system by two experiments. In the first experiment, we employ a controlled source consisting of one-turn 5 m by 5 m square coil driven by a signal generator and an audio amplifier. The receiver coil is a 16-turn 5 m by 5 m coil located 50 m away. The theoretical signal values are calculated and compared with the experimentally obtained signal values in Fig. 3. We find that the values agree with an accuracy better than 1%. In the second experiment, we perform a groundwater measurement at the Schillerschlage test site in Hannover, Germany. A Vista Clara GMR instrument was operated with a 60 m diameter circular transmit loop and 40 ms transmit pulses at pulse moments in the range 0.09 to 10 As. The receiver coil for the Vista Clara system was a 12-turn 10 m by 10 m coil. The receiver coil for our instrument was an 8-turn 10 m by 10 m coil overlaid the Vista Clara receiver coil. Our instrument is synchronized to the Vista Clara GMR by a high bandwidth current probe on the TX coil. The output from the current probe is measured by one of the receiver channels and triggers the data acquisition. The Apsu data set is scaled to the same effective area as the Vista Clara GMR data, otherwise, identical signal processing (bandpass filtering, powerline harmonic subtraction, stacking and envelope detection) were performed on the two data sets. The results are provided in Figure 4. Panel (a) and (b) in the top row shows the processed data from the two instruments. In both measurement an NMR signal is observed at pulse moments 10 to 15. In panel (c) the ratio between measurements from the two instruments is plotted. For pulse moments 10 to 15 at times less than 200 ms where the NMR signal is observed the ratio is close to one showing that the two instruments measure the same data. At other pulse moments and times where no NMR signal is present the ratio is random as expected. Panel (d) shows the envelope of data from pulse moment 12. The two systems give nearly identical envelopes and there is no structure in the difference signal.



**Figure 3: Comparison of theoretical and experimentally measured signal values from a magnetic dipole source.**



**Figure 4: Groundwater measurement comparison with Vista Clara GMR. The top row shows the processed data from the two instruments. Panel (c) shows the ratio between data from the two instruments. Panel (d) shows plots of the NMR envelope for the 12<sup>th</sup> pulse moment for both instruments and the difference signal.**

## CONCLUSIONS

We have developed a new low noise, multichannel surface NMR receiver system featuring wireless connections between data acquisition boxes. Test experiments show that the instrument performs as expected and provides NMR results on par with a Vista Clara GMR instrument. The new instrument provides a platform for further research into surface NMR and opens up for new possibilities in surface NMR fieldwork where field layout during a survey is simplified by the wireless connections. We are currently conducting further experiments with the new instruments and tailoring the signal processing to the new possibilities.

## ACKNOWLEDGMENTS

The authors are grateful to Bo Bjerre, Simon Ejlersen and Søren Møller Dath for technical assistance in the development. Denys Grombacher is funded by the Danish Council for Independent Research. Lichao Liu is supported by the China Scholarship Council. The project is funded by the COWI Foundation and by Aarhus University Research Foundation.

## REFERENCES

- Bahner, K. Larsen, J. J. and Auken, E. 2015, Multichannel magnetic resonance sounding with wirelessly operated coils – A design study. MRS 2015, 6<sup>th</sup> International Workshop on Magnetic Resonance.
- Behroozmand, A., Keating, K. and Auken, E. 2015, A review of the principles and applications of the NMR technique for near surface characterization. *Surveys in Geophysics*, 36, 27-85.

- Behroozmand, A.A., Auken, E., Fiandaca, G. and Rejckjær, S. 2016, Increasing the resolution and the signal-to-noise ratio of magnetic resonance sounding data using a central loop configuration. *Geophysical Journal International*, 205, 243-256.
- 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, 89-02.
- Jiang, C., Müller-Petke, M., Lin, J. and Yaramanci, U., 2015, Magnetic resonance tomography using elongated transmitter and in-loop receiver arrays for time-efficient 2-D imaging of subsurface aquifer structures. *Geophysical Journal International*, 200, 822-34.
- Larsen, J.J., Dalgaard, E. and Auken, E. 2014, Noise cancelling of MRS signals combining modelbased removal of powerline harmonics and multichannelWiener filtering. *Geophysical Journal International*, 196, 828-836.
- Larsen, J.J. and Behroozmand, A.A., 2016, Processing of surface-nuclear magnetic resonance data from sites with high noise levels. *Geophysics*, 81, WB75-WB83
- Radic, T. 2006, Improving the signal-to-noise ratio of surface NMR data due to the remote reference technique. *Near Surface Geoscience 2006*, 12<sup>th</sup> European Meeting of Environmental and Engineering Geophysics, EAGE.
- Semenov, A. 1987, NMR hydroscope for water prospecting. *Proceedings of the Seminar on Geotomography*. 66-67.
- Walsh, D.O. 2008, Multi-channel surface NMR instrumentation and software for 1D/2D groundwater investigations. *Journal of Applied Geophysics*, 66, 140-150.