



Surface NMR groundwater measurements with dual transmitters

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Abstract. One of the controlling factors for the depth of investigation in a groundwater measurement with surface NMR is the available excitation current. Increasing this current is generally a difficult and costly engineering challenge. In this paper, we experimentally demonstrate a different approach towards higher excitation currents. We simultaneously operate two surface NMR instruments with overlapping transmitter coils, which effectively turn them into one instrument with a maximum current twice as large as a single instrument. An analysis of the NMR excitation pulses shows that the combined pulses are very stable with negligible amplitude and timing errors. A field example is provided where data from a single instrument and from the dual instrument setup are compared. The paper contains a discussion on how this approach can be extended to novel surface NMR transmitter strategies.

1 Introduction

Surface nuclear magnetic resonance (NMR) is a fascinating geophysical method due to its ability to directly detect groundwater and provide depth-resolved data from non-invasive measurements conducted with a coil laid out on the ground (Behroozmand et al., 2015). Since it was invented, the method has been used in many hydrological investigations worldwide (e.g., Parsekian et al., 2013; Mazzilli et al., 2020; Li et al., 2020)

Unfortunately, surface NMR is generally limited by poor signal-to-noise ratios due to inherently low signal levels. Considerable amounts of research have therefore been devoted to improvements of instrumentation. One significant leap forward was the introduction of multi-channel instruments with additional receiver coils utilized for remote reference noise cancellation (Walsh, 2008).

Continued research on the surface NMR method has explored many avenues including electric bipole excitation (Davis et al., 2019), measurement of the NMR B-field with a SQUID (Davis et al., 2014), and a gradient coil to encode depth information in the NMR signal (Morozon et al., 2024). One current topic is pre-polarization methods. While limited to very shallow applications, it has important use-cases in soil moisture detection and forward-looking instruments for tunnel engineering (Hiller et al., 2021; Lin et al., 2021).

A recent addition to surface NMR instrumentation is steady-state methods (Grombacher et al., 2021). The surface NMR standard is the free induction decay (FID) where nuclear spins are excited with a typically 20-40 ms long transmitter pulse and the subsequent relaxation is measured. The nuclear spins are required to fully relax to equilibrium before the next transmitter pulse. With steady-state methods the excitation is done by a train of closely spaced, identical pulses, and the spins do not



fully relax before the next excitation. The steady-state method has significantly increased the signal-to-noise ratio and mapping speed of surface NMR measurements (Vang et al., 2023).

Various forms of advanced receiver coil geometries have been proposed, e.g., 2D layouts for tomography (Jiang et al., 2014), rotated received coils (Jiang et al., 2021), and noise-cancelling geometries (Girard et al., 2020; Kremer et al., 2020; Wang et al., 2022; Hiller et al., 2023). However, on the transmitter side, only one conference paper has touched upon an advanced layout or the use of multiple transmitter coils (Irons et al., 2016).

An important aspect of surface NMR measurements is the depth-of-investigation. This is controlled by the ability to provide an adequate field strength at depth to perturb the magnetization and by the ability to measure the subsequent relaxation. State-of-the-art instruments utilize dedicated power electronics to provide more than 600 A of current in a 100×100 m transmitter coil (Walsh, 2008). It is a significant engineering challenge to increase the depth of investigation by using larger coils and higher currents (Legchenko and Pierrat, 2014). Another route to increased depth of investigation is very long excitation pulses at low currents, but this is a power consuming approach only applicable to NMR targets with long relaxation times (Larsen et al., 2024).

Here we explore a different route towards high current measurements. Instead of increasing the maximum current of a single transmitter, we demonstrate simultaneous operation of two lower current surface NMR instruments with overlapping coils and show how this corresponds to one high current surface NMR instrument.

The outline of this paper is as follows. In Section 2 a numerical analysis of the depth of investigation versus transmitter current is presented. This is followed by a description of the experimental setup and data collection in Section 3. Results and discussion are presented in Section 4 and 5 respectively, before concluding remarks in Section 6.

2 Numerical analysis

We analyze the impact of transmitter pulse current by numerical simulations of the Bloch equation

$$\frac{d\mathbf{M}}{dt} = \gamma \mathbf{M} \times \mathbf{B} - \frac{M_x}{T_2} \hat{x} - \frac{M_y}{T_2} \hat{y} - \frac{M_z - M_0}{T_1} \hat{z}, \quad (1)$$

where γ is the gyromagnetic ratio, $\mathbf{M} = M_x \hat{x} + M_y \hat{y} + M_z \hat{z}$ the magnetization, M_0 is the equilibrium magnetization in the earth field, $\mathbf{B}$ is the transmitted magnetic field, T_2 and T_1 are the transverse and longitudinal relaxation times. Equation 1 represents a single voxel and does not explicitly show the spatial and temporal dependence of $\mathbf{M}$ and $\mathbf{B}$, the spatial variations of T_1 and T_2 in the earth layers, or the effects of inhomogeneities in the magnetic field. We numerically solve the Bloch equations on a discretized set of voxels with the Runge-Kutta-4 algorithm, and account for magnetic field inhomogeneities (Griffiths et al., 2021). Simulations are done with steady-state pulse trains with a 2164 Hz transmitter frequency corresponding to a transmitter period, T_{Tx} , of 462 μ s. Each pulse contains 40 oscillations, i.e., the pulse duration is 40 T_{Tx} or ~ 18.5 ms. The pulse repetition time is 400 T_{Tx} or ~ 185 ms. We use trains of alternating pulses, i.e., adjacent pulses have opposite polarity. All simulations are based on a 50 m $\times$ 50 m coincident transmitter and receiver coil like the experimental setup. The simulations assume a half-space with 10 % water content, $T_1 = T_2 = 300$ ms, $T_2^* = 170$ ms, and a 100 Ω m earth resistivity.

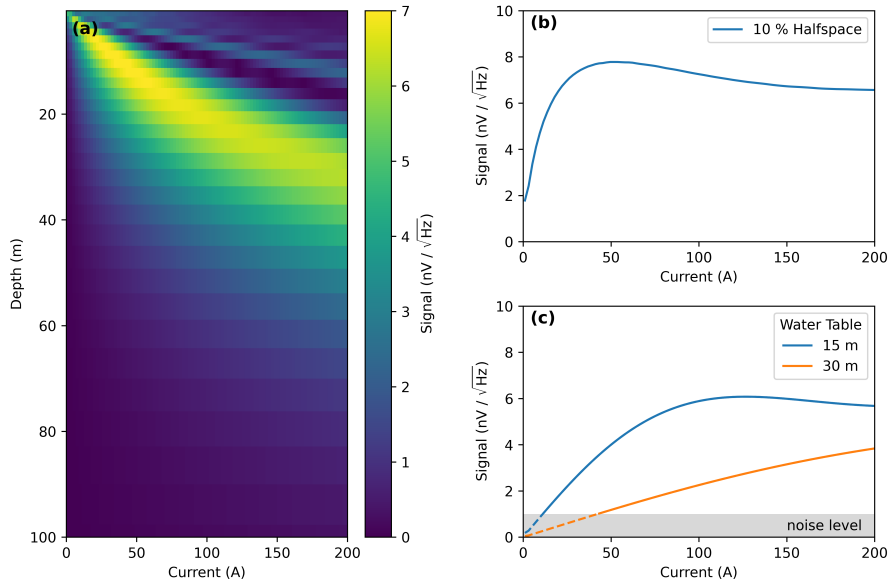


Figure 1. Numerical simulations of the NMR signal from a alternating pulse steady-state surface NMR measurement. (a) Kernel showing the contributions to the NMR signal for a 10 % water content half-space as a function of depth and current amplitude. (b) Sounding curve corresponding to (a). (c) Sounding curves for groundwater tables at 15 m or 30 m depth. The gray area indicates a $1 \text{ nV}/\sqrt{\text{Hz}}$ noise level.

Figure 1(a) is a key result. It shows the contribution to the NMR signal from different depths intervals for currents between 0 A and 200 A. As such the result is unsurprising; the diagonal structure in the map shows that when the current is increased, the range contributing to the NMR signal moves deeper and expands. Using the peak of the distribution as a very coarse proxy for depth, we see that at 50 A, most of the NMR signal originates from a depth of ~ 15 m, while at 100 A, the depth is ~ 25 m. As the current is increased further, the peak of the distribution continuously moves deeper, but at a decreasing rate. This result matches with a previous study of factors influencing the depth of steady-state signals but uses a larger current range relevant for this work (Grombacher et al., 2024a).

Another visualization is given in Fig. 1(b) where we show a standard sounding curve, i.e., the initial amplitude of the received NMR signal as a function of the current. The sounding curve increases smoothly up to about 50 A where it peaks at almost $8 \text{ nV}/\sqrt{\text{Hz}}$ and slowly decreases to a plateau of about $6 \text{ nV}/\sqrt{\text{Hz}}$. In Fig. 1(c) we contrast the sounding curves for two interesting cases where a groundwater table with 10 % water content is located at a depth of either 15 m or 30 m. The figure also includes a $1 \text{ nV}/\sqrt{\text{Hz}}$ noise level shown in gray. Only signals with amplitudes exceeding the noise level will be observable. For the case of a water table at 15 m the signal rises above the noise level at 10 A, whereas for a water table at 30 m, 50 A is needed for detection. This example is based on a particular earth model and coil layout, but the conclusion is generally applicable: larger currents allow for detection of groundwater at greater depths.

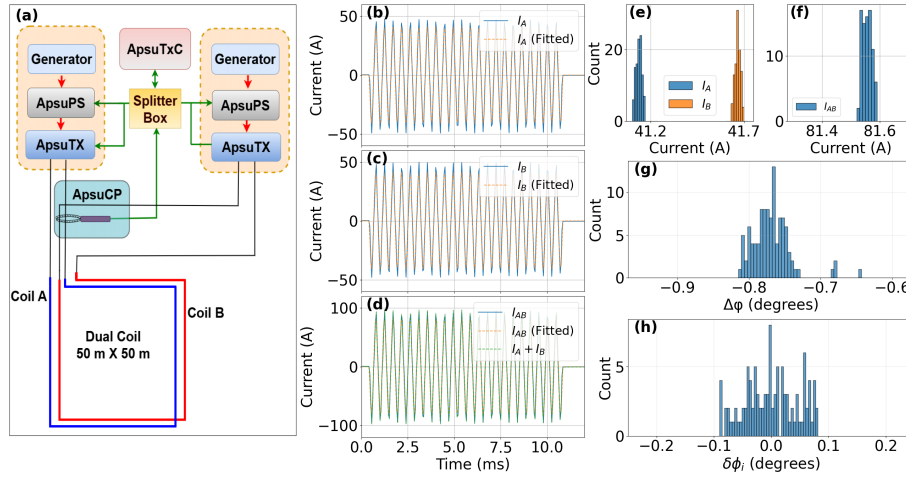


Figure 2. (a) Block diagram of the experimental setup. (b-d) Synchronous current measurements in coil A, coil B, and coil A+B. (e-f) Pulse amplitude histograms. (g) Phase difference histogram between coil A and coil B pulses. (h) Phase difference histogram between transmitted pulses.

3 Experimental setup and data collection

75 The experimental results are obtained using two Apsu surface NMR instruments (Larsen et al., 2020; Gaikwad et al., 2025). Apsu is a home-built surface NMR instrument used with a 50 m × 50 m transmit and receive coil. The instrument is designed in modules connected by cables. The transmitter unit, ApsuTX, contains an H-bridge for pulse generation. The transmitter unit is connected to ApsuPS, which contains a 600 V, 1 A power supply charging a 10 mF capacitor bank. Energy is obtained from a 2 kW gasoline generator. The transmitter unit is connected to the transmit and receive coil through ApsuCP, which contains

80 a current probe for measuring the transmitter pulses and a diode clamping circuit for conditioning the surface NMR signal. The on-off signals for the H-bridge and the voltage settings for the power supply are generated in the control unit, ApsuTXC. Surface NMR signal amplification, filtering, and analog-to-digital conversion also take place in ApsuTXC. The modularity of the instrument is utilized here to couple two instruments with two coils, denoted A and B, together as shown in the block diagram, Fig. 2(a). The control signals from the ApsuTXC unit are split in two and also directed to a second ApsuPS / ApsuTX

85 connected to coil B. It is not possible to independently measure the current in coil B. Instead, this coil is also routed through the current probe in ApsuCP, which therefore measures the total current, I_{AB} in both coils. Likewise, it is only possible to measure the surface NMR signal in coil A. Effectively, the dual coil setup acts as a single coil measurement, only with a higher maximum current due to the additional transmitter unit and transmitter coil. Data are collected and processed with our standard software (Liu et al., 2023).

90 The pulse train stability of the dual transmitter setup was verified by synchronous measurements of the currents in coil A, coil B, and coil A+B with three current clamps connected to a multichannel digital oscilloscope. The result for a single 10 ms pulse is presented in Fig. 2(b-d). The solid blue lines in Fig. 2(b) and Fig. 2(c) show the currents I_A and I_B . Fig. 2(d) shows the



synchronous measurement of I_{AB} (solid line) together with the sum current $I_A + I_B$ (dashed green line). As seen in Fig. 2(d), the sum of the individual currents I_A and I_B gives the same results as measuring them together directly, which confirms that the two channels combine linearly.

An analysis of the pulse train stability is conducted by fitting the current of the i 'th pulse in a 10 s long pulse train with 105 pulses to the expression $I_i(t) = A_i \sin(2\pi f_L t + \phi_i)$. The fitted currents are plotted as dashed orange lines in Fig. 2(b-d) where the measured waveforms are seen to match the fitted signal for I_A , I_B , and I_{AB} with small discrepancies caused by the non-sinusoidal pulse shape (Larsen et al., 2020; Gaikwad et al., 2025). The sets of fitting parameters $\{A_i\}$ and $\{\phi_i\}$ are also used to derive distributions of pulse amplitude and phase, Fig. 2(e-f). The mean amplitudes are 41.13 ± 0.02 A and 41.66 ± 0.04 A for I_A and I_B and 81.67 ± 0.03 A for I_{AB} , i.e., we observe very little variation in pulse-to-pulse amplitude and the amplitudes from each coil are almost equal. In Fig. 2(g) we show a histogram of the phase differences $\Delta\phi_{AB} = \phi_B - \phi_A$. The mean phase difference is -0.77 ± 0.03 degrees. The small phase difference implies that the two pulse trains in coil A and B combine effectively into one high current pulse train. Likewise, the small standard deviation shows that there is little timing jitter. Another important indicator of pulse train stability is the timing between adjacent pulses in the pulse train (Gaikwad et al., 2025). We compute a phase difference between adjacent pulse, $\delta\phi_i = \phi_{i+1} - \phi_i$ and plot a histogram of the difference between $\delta\phi_i$ and its mean value in Fig. 2(h). The standard deviation is 0.05 degrees implying negligible timing errors between pulses.

Experimental data are collected at Kompedal, Denmark. This is a 23 km² plantation area with large open fields, and it has excellent low-noise conditions. The site is composed of a thick sand package deposited by meltwater on top of a till layer yielding a large, unconfined aquifer with a water table ranging between 2 m and 14 m (Vang et al., 2023; Griffiths et al., 2024). The local magnetic field was measured with a proton magnetometer and used to set 2164 Hz as the transmitter frequency throughout all measurements.

Data sets were collected for a standard single coil setup and for the dual coil setup. For single coil data we used four different current amplitudes from 4 A to 52 A and for the dual coil setup we used eight different current amplitudes from 4 A to 114 A where the four lowest amplitudes were matched to the single coil currents to within ± 2 A. We used trains composed of alternating pulses with pulse lengths of $20 T_{Tx}$, $40 T_{Tx}$, and $80 T_{Tx}$ (approximately 10 ms, 20 ms, and 40 ms) all with a 10 % duty cycle. For each combination of pulse duration and current 60 s of data were collected and analyzed.

4 Results

Figure 3 shows results for $40 T_{Tx}$ and $80 T_{Tx}$ pulses. A frequency analysis of data from a $40 T_{Tx}$, 35 A single coil measurement are shown in blue in (a) and data from a $40 T_{Tx}$, 35 A dual coil measurement are shown in orange in (c). The two measurements are seen to be almost equal as expected and both contain a strong NMR peak at 2164 Hz. Our processing workflow estimates the instantaneous Larmor frequency in a 60 second measurement with an uncertainty of about 0.2 Hz. The estimates are indicated with triangles and reveal variations in the Larmor frequency between measurements. Variations are expected as the two data sets are collected about one hour apart. The spectra also contain two small spikelets ~ 5.4 Hz above and below the main peak.

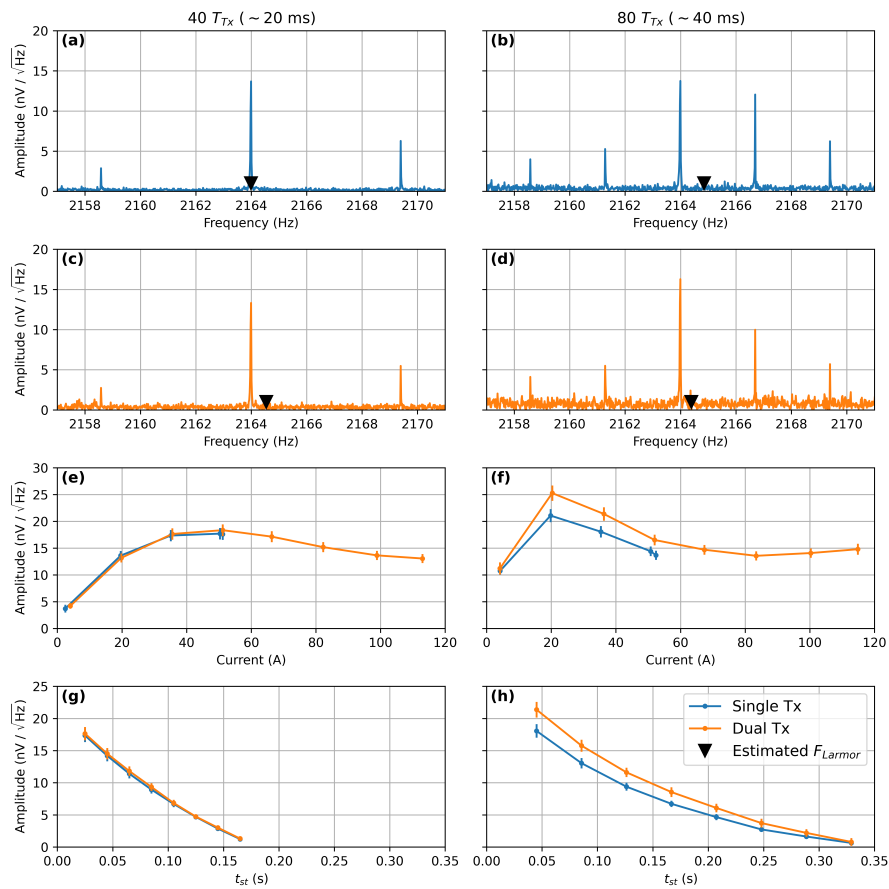


Figure 3. Surface NMR data from Kompedal. The left and right columns show results for $40 T_{Tx}$ and $80 T_{Tx}$ pulses color coded with blue for single coil data and orange for dual coil data. (a-d) Frequency spectra for 35 A transmitter pulses with the NMR signal peak at 2164 Hz and spikelets at offset frequencies. Black triangles show instantaneous Larmor frequency estimates. (e,f) Sounding curves. (g,h) Spectral analysis decay curves for 35 A data.



These are due to the 185 ms repetition time of the pulse train (Grombacher et al., 2024b). Panel (e) shows the sounding curves for the single and dual coil data. We observe a very good agreement in the range where the currents overlap and a smooth sounding curve for the four additional dual coil currents like what is observed in Fig. 1. Panel (g) plots the spectral analysis decay curve of the signals from panel (a) and (b). The two curves overlap almost perfectly, showing that single coil and dual coil measurements give identical results.

However, for longer pulses, offsets between the transmitter frequency and the Larmor frequency will have a larger impact and can give visibly different results. An example is found in the right-hand column of Fig. 3 where we plot results for 80 T_{Tx} (approximately 40 ms) pulses. In the single coil case (b), the estimated Larmor frequency is ~ 0.8 Hz larger than the transmitter frequency and in the dual coil case (d) it is only ~ 0.4 Hz. This difference gives rise to different signal levels as observed on (b,d) and on the sounding curve in (f). Importantly, the spectral analysis decay curves in (h) show that the single and dual signals still relax at approximately the same rate. As such, off-resonance excitation is not a problem as it is estimated during processing and included in inversion (Liu et al., 2023). Spikelets are again observed for the 80 T_{Tx} pulses, but the distance to the main peak is halved as the repetition time is doubled. Second order spikelets are now also visible.

Three data sets are inverted with smooth regularization and vertical constraints of 0.4 for all parameters (Griffiths et al., 2024): single coil data (blue), dual coil data culled to the same four currents as single coil data (orange dashed), and the full dual coil data set with all eight currents (orange). Depth profiles of water content and T_2 are shown in Fig. 4(a,b) along with results (black) from NMR borehole logging (Griffiths et al., 2024). Panels (c-e) compare the observed and modeled data where data are grouped by pulse type and each set of data points / line is a spectral analysis decay curve for a specific current (Griffiths et al., 2022). The single and dual coil data from (c) and (e) are plotted on top of one another in (f) for easy visual inspection. Several important conclusions can be drawn from the plots. First, the single coil and the culled dual coil data sets give visible indistinguishable results for both water content and T_2 . Second, all three data sets agree very well on the depth of the groundwater table at about 7 m in concordance with the borehole log. They also agree well on the water content below the groundwater table, but they all estimate a lower water content than measured with the borehole NMR logging.

For the T_2 results, we again observe a near perfect agreement between the single coil and the culled dual coil data sets. However, the full dual coil data set departs somewhat from the other data sets and provides T_2 estimates closer to the borehole NMR log in 15 m to 30 m range. The comparison of data and models in panel (c)-(f) show that the retrieved models all fit the data very well within the error bars and the observed differences are therefore reasonable.

The inversion code estimates the depth of investigation. This comes out as 40 m for the single coil data set and 45 m for the dual coil data with a current range twice as large. The increase is smaller than would be expected from the results in Fig. 1. The likely reason for this somewhat odd result is that the till layer beneath the sandy aquifer starting at a depth of about 35 m does not contribute to the NMR signal (Vang et al., 2023; Griffiths et al., 2024). This till layer can also explain the discrepancy between borehole and surface NMR water content, i.e., if the inversion lacks the ability to resolve the sharp boundary of the aquifer, it can over- and underestimate the water content below and above the boundary. As such, this data set is therefore a good example of the challenges in interpreting surface NMR data.

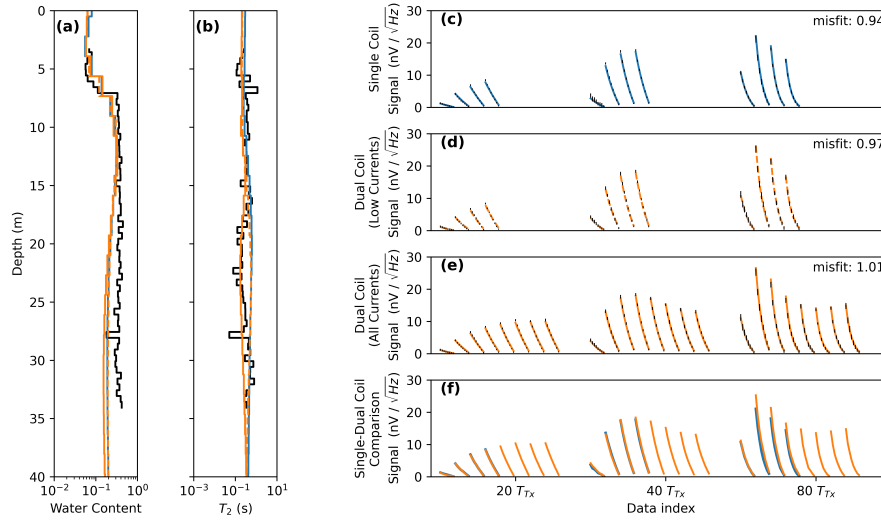


Figure 4. Inversion results for single coil data (blue), dual coil data culled to low currents (dashed orange), and the full set of dual coil data (orange). NMR borehole logs are shown in black. (a) Water content. (b) T_2 profile. (c-e) Data and models. Error bars on data are indicated with black lines. (f) Comparison of single coil and dual coil data.

160 5 Discussion

The performance of the dual coil approach hinges on the stability of the pulse trains. If there is a timing error in one transmitter relative to the other transmitter, the pulse trains will get out of phase. At low errors, this will only lead to a slightly lower total amplitude, but if the error is large the two pulse trains can in a worst-case scenario have opposite phases and lead to a very small current. The results shown in Fig. 2 demonstrated that driving the two surface NMR transmitters from the same control signals is an efficient way of creating pulse trains with stability on par with a single instrument (Gaikwad et al., 2025). It should be noted that the two instruments are not fully independent, as there is an electromagnetic coupling between the two transmitter coils. One example of this is the maximum current that could be transmitted in this experiment, i.e., for the single coil $I_{max} = 52$ A, but for the dual coil setup we observe $I_{max} = 114$ A, which is 10 % higher than 2×52 A. The likely reason for this small increase is that the electromagnetic coupling corresponds to a slight tuning of the coils.

For this first demonstration, we have coupled two surface NMR transmitters together. There is nothing preventing that even more transmitters are operated in unison to provide even higher currents and larger depth of investigation, but the availability of instruments and field logistics will impose constraints. In the context of our instrument, one aspect is also that its maximum voltage is 600 V and this imposes a limit on how large transmitter coils that can be used due to the increased self-inductance of larger coils requiring higher voltages. In standard cases, a single high-voltage transmitter operated with a large coil will therefore be the first choice for achieving depth of investigation. Importantly, our approach suggests a new research path where



two or more transmitter coils are laid out in other geometries and the pulse trains in each coil are individually adjusted to obtain tailored NMR excitation patterns in the earth.

Our experimental demonstration is based on steady-state pulse trains. We emphasize that our approach is equally feasible for any other surface NMR acquisition scheme such as free induction decay (FID) measured. We have only collected steady-state data as we believe this is a superior method with, e.g., higher signal-to-noise ratio and direct inversion for T_2 values. However, in the limit of long pulse repetition times, nuclear spins will fully relax between transmitter pulses, and the steady-state scheme turns into standard FID. Our approach is therefore also directly applicable to FID measurements.

The inversion results presented in Fig. 4 clearly demonstrated that data collected with dual transmitter coils are identical to data collected with a single transmitter coil. Our inversion results are in fair agreement with the borehole logging results, but the expected increase in depth of investigation is challenged by the till layer below the aquifer (Griffiths et al., 2024). It should be noted that for this demonstration we have collected a small data set containing only on-resonance alternating pulses. It is beyond the scope of this paper, but it is possible that the collection of an expanded data set including for example regular pulses or off-resonant pulses sampled at more current amplitudes and inversion with methods emphasizing boundaries can improve the consistency between the methods.

6 Conclusions

We have demonstrated how two low-current surface NMR instruments can be operated together as a single instrument with a current range twice that of a single instrument. Barring economy and experimental or logistic constraints, the method can be extended to more than two surface NMR instruments providing even higher currents. Forward going, our work opens for new surface NMR research where non-coincident coils are used with individually adjusted pulses in each coil for novel spatial control of the NMR excitation.

Data availability. The surface NMR data set is available at Griffiths (2026).

Author contributions. SG: Experimental design, data acquisition and analysis. MG: Data acquisition and analysis, modeling and inversion. MH: Data analysis. JLL: Funding acquisition, conceptualization, supervision, writing.

Competing interests. The authors declare that they have no competing interests.

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