Development of Adiabatic Pulses to Enhance Speed and Sensitivity of Surface NMR Measurements

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SUMMARY

We present a new approach to improve the sensitivity and efficiency of geophysical surface nuclear magnetic resonance (NMR) measurements. An extremely powerful tool in groundwater investigations, surface NMR inherently has a relatively low signal-to-noise ratio (SNR), which sometimes necessitates long survey times for signal averaging. In pursuit of faster survey speeds, we show that replacing the standard on-resonance excitation pulse with an adiabatic, frequency-swept pulse can provide significant increases in the NMR signal amplitude. This increase results from the fact that adiabatic pulses can excite larger volumes of groundwater more efficiently than conventional pulses. Using numerical simulations and full-scale field experiments, we show that adiabatic pulses can provide a factor of ~3 increase in signal, and suggest other advantages for groundwater imaging. The signal increase alone allows for data of equivalent SNR to be acquired in a fraction of the time required for conventional on-resonance pulses. Ultimately these improvements can allow surface NMR to be exploited in an expanding range of applications.

Key words: Surface Nuclear Magnetic Resonance, NMR, Groundwater, Aquifer Characterization, SNMR, MRS, Porosity, Permeability

INTRODUCTION

Surface NMR offers the unique capability to non-invasively detect groundwater and characterize aquifer flow and storage parameters. Considering the high value of surface NMR data, there is a compelling motivation to develop approaches that can enhance measurement efficiency and sensitivity. In recent years, the development of multi-channel adaptive noise cancellation (Walsh, 2007) has allowed major improvements in the SNR, reducing signal averaging times; multi-pulse sequences have cut the number of parameters that must be varied between acquisitions (Grunewald and Walsh, 2013); and varied transmitter-receiver array geometries have been suggested to simplify 2D recordings (Jiang, 2013). While these advancements have accelerated acquisition speeds, survey times on the order of hours are not uncommon and further acceleration is important to broaden the range of applications adopting this valuable geophysical method.

To this aim, we present a new approach that yields significant improvements in sensitivity and efficiency by activating signal from larger and more uniform volumes of the subsurface. Our approach leverages pulse designs previously employed in medical MRI (e.g. Tannus and Garwood, 1997). Specifically, we replace the transmitted excitation pulse, conventionally a fixed-frequency "on-resonance" pulse, with an amplitude- and frequency-modulated "adiabatic" pulse.

We illustrate our approach with numerical simulations and demonstrate performance with field data acquired using adiabatic pulses. Results show this approach provides significant improvements in SNR and yields excitation profiles that may offer improved imaging resolution. In practice, these improvements are estimated to enable survey time reductions on the order of 70-90%, supporting expansion of surface NMR into new applications.

METHOD AND RESULTS

NMR Excitation Pulses

An NMR measurement operates by exciting a response from the nuclear magnetization associated with hydrogen nuclei in fluids. In a static background magnetic field B_0, the net nuclear magnetization M is polarized parallel to B_0 (in the "longitudinal z-direction"). In this equilibrium state, the DC magnetization is too small to detect but it can be excited away from equilibrium by applying a second oscillating magnetic field pulse B_1, perpendicular to B_0, and tuned near the Larmor frequency $f_0 = \gamma \cdot B_0$ ($\gamma/2\pi$ = 4257 Hz/G).

This B_1 excitation pulse causes the magnetization to shift away from the longitudinal axis, rotating a component of the magnetization into the "transverse x-y" plane. When the pulse is extinguished, the coherent magnetization left in the x-y plane M_{xy} will precess about B_0, generating a detectable signal that oscillates at the Larmor frequency. The amplitude of the resulting signal depends not only on the magnitude of M (quantity of hydrogen excited) but also the degree to which the B_1 excitation pulse rotates the magnetization into the transverse plane.

The evolution of this rotation in response to the excitation pulse is illustrated schematically in Figure 1. The left panel shows the case of a conventional on-resonance pulse, where the pulse is transmitted exactly at the Larmor frequency. In this on-resonance condition, the effective field and rotation axis B_{eff} (red) is aligned in the transverse plane. While the pulse is on, the magnetization (black stars) follows a circular path about this nutation axis over the duration of the pulse. In this depiction, the final rotation is an ideal 90º tip angle, putting the magnetization entirely into the transverse plane. The actual tip angle depends upon the magnitude of the pulsed

B_1 field and the pulse duration: $M_{xy}/M=\sin(\gamma \cdot B_1/2 \cdot t_{pulse})$. If the pulsed field is weak, the tip angle will be small; if the pulsed field is very strong, the tip angle may be much more than 90º or even 360º, yielding a wide possible range of M_{xy} for different B_1 amplitudes.

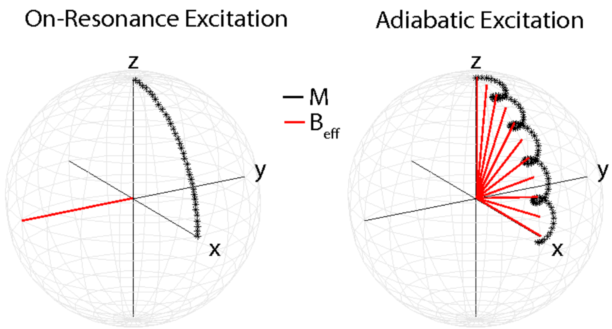

Figure 1. Representation of magnetization evolution during excitation by an on-resonance (left) and adiabatic (right) pulse.

A very different rotation evolution is produced by an adiabatic pulse, shown in the right panel of Figure 1. In the adiabatic half passage AHP pulse (Bendall and Pegg, 1986), the frequency of the pulse F(t) is swept from off-resonance ($F(0)<<f_0$) to the on-resonance Larmor frequency; the amplitude of the pulse may also be modulated. As depicted, the effective field and rotation axis B_{eff} begins parallel to the longitudinal axis when $F(t)<<f_0$. As F(t) comes on resonance, B_{eff} pivots downwards, eventually stopping in the transverse plane when fully on-resonance. As this axis pivots, the magnetization nutates about B_{eff} in a spiral (adiabatically), following B_{eff} toward the final position in the transverse plane.

The primary advantage of an adiabatic pulse is the resulting tip angle is much less sensitive to the amplitude of the B_1 pulse, so uniform tip angles can be produced for a wide range of B_1 amplitudes. To exhibit such behavior, the "adiabatic condition" must be satisfied: i.e., the angular rate of nutation about the B_{eff} axis must be much greater than the angular rate at which the B_{eff} axis pivots. Details regarding selection of amplitude and frequency modulation functions to satisfy the adiabatic condition can be found in Tannus and Garwood (1996).

Adiabatic Pulses for Surface NMR

In a geophysical surface NMR survey, the background magnetic field is Earth's geomagnetic field, and surface coils are used both to transmit the excitation pulses and to measure the resulting NMR signals. Because the coil is located at the surface, the subsurface B_1 fields are grossly inhomogeneous, decreasing with depth away from the coil. As a result, the subsurface distribution of tip angles and excited transverse magnetization is strongly influenced by the pulse characteristics.

Calculated by numerical simulations, Figure 2 shows a subsurface north-south slice of the excited transverse magnetization resulting from a conventional on-resonance and adiabatic pulse; the surface coil is 25m diameter. The on-resonance pulse induces very inhomogeneous excitation, given the grossly inhomogeneous B_1 field. In particular, close to the coil, the strong B_1 values induce tip angles cycling multiple rotations leaving incoherent transverse magnetization. Coherent excitation that produces detectable signals occurs primarily in a lower portion of the subsurface, where the B_1 amplitude is modest and generates tip angles closer to 90º ($M_{xy}=1$ in Figure 2)

A stark contrast is seen in the case of the adiabatic pulse. In this case, the pulse is 60ms with a linear frequency sweep from f_0-200Hz to f and no amplitude modulation. Here, in the presence of the same inhomogeneous B_1 field, the excitation pattern is much more uniform. Maximum transverse magnetization (i.e. tip angles near 90º) is observed over a much larger volume, resulting in larger amplitude coherent groundwater signals. For typical transmit current strengths, we find that the signal increases by approximately a factor of three for the adiabatic case compared to the on-resonance case.

In addition to generating a larger coherent signal, we also note that the excitation pattern is much less complex for the adiabatic case. As such, adiabatic pulses provide simpler kernel functions that may improve stability and resolution of imaging inversions.

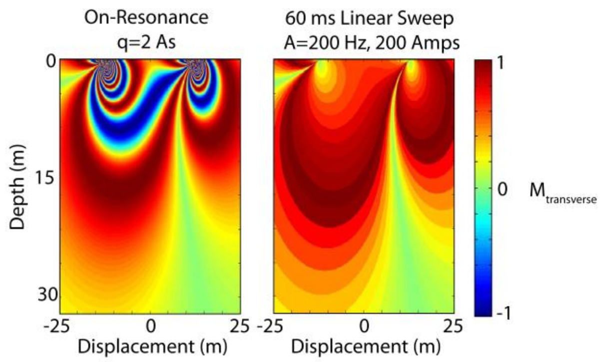

Figure 2. Numerical simulation results showing a subsurface north-south slice of the excitation profiles resulting from an on-resonance pulse (left) and adiabatic pulse (right).

Adiabatic pulses have other important advantages. In addition to tolerance to B_1 inhomogeneity, adiabatic pulses also provide more uniform excitation across volumes with B_0 magnetic field heterogeneity (e.g. associated with large-scale regional magnetic gradient or pore-scale gradients associated with magnetic mineralogy). Further, adiabatic pulses are not subject to T_2* dephasing during the pulse, which can reduce the SNR signal amplitude observed following on-resonance pulses; they are, however, still subject to T_2 relaxation during the pulse.

Surface NMR Field Results for Adiabatic Pulses

We have acquired field data using adiabatic pulses to validate the practical advantage of this approach. Initial data were acquired in August, 2014 at a site in Western Washington, USA. The site is known to have a shallow water table and significant magnetic mineralogy. A ~2m clay sequence covers a ~18m thick sand and gravel aquifer, underlain by a clay.

A single-pulse (FID) pulse sequence was programmed with a linear sweep adiabatic pulse on the multi-channel GMR instrument, manufactured by Vista Clara, Inc.. Data were acquired using a two-turn 44m circular loop with one reference loop for noise cancellation. Tests were conducted with different pulse parameters, using varied frequency sweep ranges and pulse durations). On-resonance datasets from the same site provide a direct comparison, shown in Figure 3.

For the on-resonance case, we show the average amplitude signal that was observed over a range of on-resonance pulse amplitudes (coil current) for a 20ms pulse. For the adiabatic pulse we show the signal following an adiabatic pulse using similar current but swept over 200Hz in 80ms. The environmental noise level was slightly higher during acquisition of the adiabatic data.

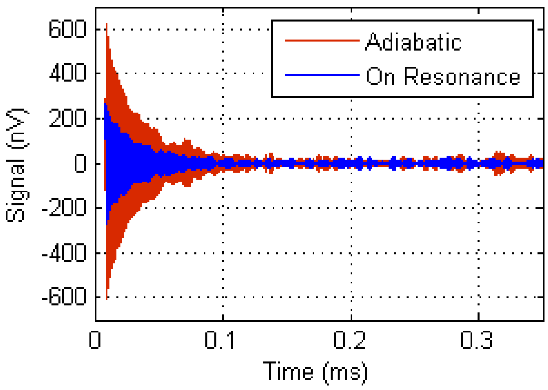

Figure 3. Field data comparing surface NMR signals resulting from an on-resonance (blue) versus adiabatic (red) pulse.

Here we observe that the signal amplitude following the adiabatic pulse (~600 nV) is nearly three times greater than that for the on-resonance pulse (~200 nV). The decay time of for the adiabatic signal is also slightly shorter, an observation which is consistent with the adiabatic pulse having a wider effective excitation bandwidth in the presence of B_0 field inhomogeneity, here induced by local magnetic mineralogy.

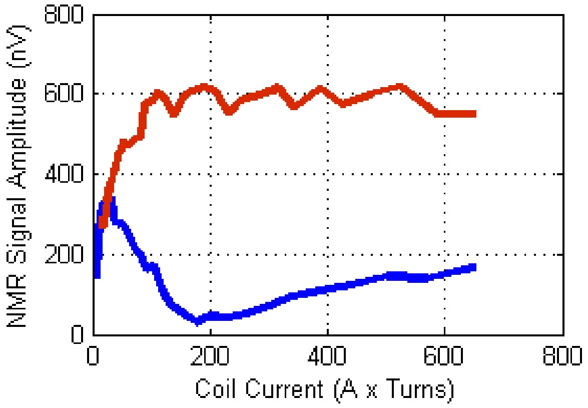

Figure 4. Field data comparing the NMR signal amplitude versus pulse amplitude from an on-resonance (blue) versus adiabatic (red) pulse.

In Figure 4, we show the effect of varying the pulse current on the resulting NMR signal amplitude. The procedure of varying the pulse amplitude or pulse moment, is a standard approach in on-resonance NMR surveys, where the variance in NMR signal with pulse amplitude is used to resolve variations in depth. The sensitivity of the on-resonance dataset to the top and bottom of the sand aquifer is indicated by an increase in the signal amplitude, peaking at low current amplitude, and then sharply decreasing as tip angles in the shallow aquifer start to greatly exceed 90°. The adiabatic dataset indicates sensitivity to the top of the aquifer, with an initial increase in signal amplitude for small pulse current. The signal response eventually levels at a maximum amplitude of ~600nV, and remaining relatively constant as the pulse amplitude is increased.

The field results confirm that the adiabatic pulse should be much more efficient than the conventional on-resonance pulse for detecting groundwater. The observed factor of three increase in signal amplitude provides a SNR ratio which would otherwise require a factor of ~9 (3^2) increase in measurement time to achieve by stacking. Conversley, the adiabatic pulse can provide a similar SNR to the on-resonance pulse in 1/9th the number of averages, effectively providing a reduction in survey averaging time of more than 85%.

Moreover, we note that during the on-resonance pulse survey, much of the survey time is spent acquiring data at pulse amplitudes for which the NMR signal is very low, and the peak signal amplitude is only found for a narrow range of pulse amplitudes. For the adiabatic pulse, a peak NMR signal amplitude can be readily obtained simply by transmitting at the maximum pulse amplitude. Thus, for the purpose of primary detection of groundwater, the use of a single adiabatic pulse can provide multiple orders of magnitude increase in surveying efficiency supporting rapid scanning deployment of surface NMR.

CONCLUSIONS

In this study, we have shown that adiabatic pulses offer a tremendous advantage in geophysical surface NMR measurements. These pulses allow much larger volumes of the subsurface to be excited in the presence of inhomogeneous B-fields. By–exciting larger volumes, these pulses can yield a marked increase in the recorded signal amplitudes. The resulting increase in SNR provides more robust detection and ultimately shorter acquisition times. Other advantages of adiabatic pulses include simpler imaging kernels and an opportunity to generate more specific excitation patterns by varying the amplitude and frequency modulation functions. Use of multi-pulse sequences incorporating adiabatic pulses are expected to provide further enhancement in the depth resolution of NMR signals and NMR relaxation time behaviour.

We note that adiabatic pulses will likely be most useful for relatively shallower survey. This is because relatively strong B_1 amplitudes are required to satisfy the adiabatic condition. On-resonance pulses are likely to be more efficient than adiabatic pulses for exciting signals from depths greater than 50-60m. The combined acquisition of both adiabatic and on-resonance datasets in an integrated approach, however, can allow the advantages of both techniques to be exploited.

ACKNOWLEDGMENTS

We are grateful to the Washington Department of Fish and Wildlife for allowing access to the field site. We also thank Elizabeth Clark for providing field assistance.

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