Development of Rapid Scanning Surface-NMR for Wide Area Hydrogeologic Mapping

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SUMMARY

Surface nuclear magnetic resonance (Surface-NMR) measurements hold the valuable capability to directly image groundwater and to characterize aquifer flow and storage properties. Historically, implementations of surface-NMR have been limited by long stacking times and slow survey deployment, restricting applications primarily to 1D soundings and short 2D profiles. Through advancements in acquisition schemes, hardware, and deployment platforms, we demonstrate the ability to deploy surface-NMR as an efficient wide-area mapping technique. To increase measurement efficiency, we have developed acquisition schemes to improve the inherently low signal-to-noise-ratio of Earth's field NMR. Adiabatic pulse sequences are used to increase the detected NMR signal amplitude and to reduce requirements to scan over a wide range of pulse moments. Newly developed wireless noise-reference coil stations are used to cancel environmental noise without increasing the size or footprint of the signal-detection array. Smaller footprint wired signal-detection arrays are transported efficiently using mobile platforms, including towed coil mats and elevated coil forms. The detection array can be moved along a profile line and left in a static position for short time intervals to acquire measurements before being moved to the next position. These newly developed rapid scanning NMR technologies are demonstrated at a collection of sites in the Western United States.

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

INTRODUCTION

Surface-NMR is a uniquely powerful technology in its ability to non-invasively detect groundwater and characterize aquifer flow and storage parameters. The adoption and application of the technique, however, have been limited in practice by slow measurement speed and cumbersome survey configuration. For these reasons, surface NMR surveys are often limited in scope to sparse 1D soundings or short 2D profiles.

Appreciating the value of surface-NMR data, there is a strong motivation to enhance measurement efficiency, and in the past decade, a number of important developments have occurred. Multi-channel adaptive noise cancellation (Walsh, 2007) has allowed major improvements in SNR, dramatically reducing signal averaging times and survey success rates. Multi-pulse sequences have reduced the number of parameters that must be varied between acquisitions (Grunewald and Walsh, 2013). Varied transmitter-receiver array geometries have also been demonstrated to simplify and accelerate short-line 2D surveys (Jiang, 2013).

While these advancements have accelerated acquisition speeds, survey times often remain on the order of hours. Our aim is to make surface-NMR a rapid and wide area mapping tool, reducing survey times by at least an order of magnitude. Such an enhancement to efficiency will reduce cost and increase survey scope, ultimately broadening the adoption and application of this valuable geophysical method.

We present advancements that dramatically enhance survey efficiency. First, we demonstrate the novel use of adiabatic pulses, which improve the inherently low signal-to-noise ratio of surface-NMR measurements and thus shorten data stacking times. Instrument developments are also presented to enhance system mobility, including the development of wireless noise-reference modules. Finally, flexible and mobile coil platforms are present that allow surface coils to be rapidly transported across large mapping areas. These approaches are demonstrated for shallow aquifer mapping at field sites in the United States.

ADIABATIC PULSES

A surface NMR measurement utilizes one or more large surface coils to excite and measure surface NMR signals. Transmitting an AC current pulse through the coil creates a magnetic field at depth, which excites the nuclear magnetic moment associated with hydrogen in fluids. When the pulse is extinguished, the excited magnetization will undergo a precession at the Larmor frequency generating an oscillating magnetic field that is detected on the surface coil. Both the Larmor frequency and the magnetization amplitude are proportional to the strength of the background magnetic field, which for surface-NMR is the weak geomagnetic field. Detectable signals are only achieved by exciting large volumes of groundwater and minimizing interfering noise.

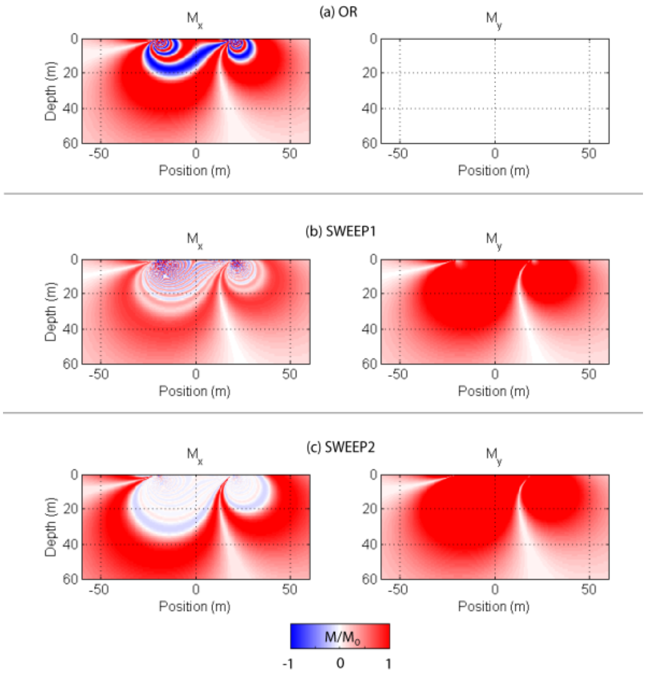

Figure 1. Subsurface excitation patterns showing the excited x- and y- components of magnetization for an a) on-resonance pulse b) adiabatic chirp sweep, and c) hyperbolic tangent sweep.

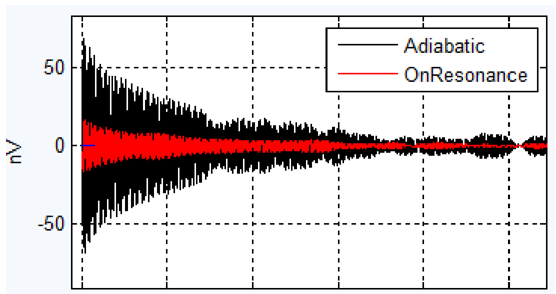

Figure 2. Field surface-NMR data comparing the mean NMR signal amplitude measured using an on-resonance pulse (red) and an adiabatic pulse (black).

Previously, surface-NMR measurements have followed a convention of using only "on-resonance" excitation pulses. An on-resonance pulse is one that is tuned to the Larmor frequency. The on-resonance condition allows use of short pulses, but produces subsurface excitation patterns that are highly variable in the subsurface. Figure 1a shows the excited NMR magnetization (with x- and y-components) resulting from an on-resonance pulse. The magnetization pattern is oscillatory with depth producing deconstructive interference and a net reduction in the NMR signal amplitude that will be measured.

In order to produce more uniform excitation patterns and larger signal amplitudes, Grunewald et al. (2015) introduced surface-NMR measurements using adiabatic pulses, a class of NMR pulses more common in medical MRI. An advantage of adiabatic pulses is that they can produce much more uniform excitation patterns, coherently exciting large volumes of the subsurface, and thus inducing large signal amplitudes. We explore the use of adiabatic pulses that are swept in frequency from off-resonance to on-resonance. Figure 1b and 1c show excitation patterns resulting from two different adiabatic pulses: SWEEP1 uses a linear "chirp" and SWEEP2 uses a hyperbolic tangent sweep.

The more uniform excitation pattern from these pulses results in signal amplitudes that can be a factor of three or greater than the signal resulting from an on-resonance pulse larger than an on-resonance pulse. The results in Figure 1 are for numerical simulations of the excitation process. In Figure 2, we show actual field results comparing the mean NMR signal measured using an on-resonance pulse and a linear chirp pulse at a site with a shallow water table. A collection of field results confirms the dramatic increase in signal amplitude resulting from the use of an adiabatic pulse.

We note that increasing the signal amplitude by a factor of N allows data with equivalent SNR to be acquired N^2 times faster. Thus even a modest SNR enhancement of a factor of three can allow for nine times faster survey speed. Combining adiabatic, on-resonance and multi-pulse sequences can further increase signal amplitude and sensitivity to subsurface hydrogeologic properties.

WIRELESS NOISE-REFERENCE STATIONS

While adiabatic pulses can be used to increase signal amplitude, the other approach to increasing SNR is reducing noise levels. For surface-NMR measurements, cultural electromagnetic noise and natural sferics can often be many orders of magnitude larger than the NMR signals. A strategy that has proven very effective for mitigating noise is the use of multi-channel remote reference loops (e.g. Walsh, 2008). In this strategy, secondary reference coils are placed away from the main detection loop -- close to the noise source (e.g. powerlines, houses, infrastructure) – in order to accurately measure background noise. Synchronized reference noise recordings are then used with adaptive filtering techniques to subtract noise from the main detection channel.

Noise reduction and SNR improvement afforded by the use of noise reference stations can be dramatic, however this approach has practical implications for measurement speed. In addition to deploying a main detection coil, reference coils must be deployed, collected, and moved when the detection coil position is significantly changed. When reference loops are moved, not only does the coil have to be collected and redeployed, but the physical lead outs to the coil must also be moved. Typically lead outs to reference coils are long to maintain large separation distances from the detection loop and to avoid cancelling NMR signal.

To overcome this physical constraint, we demonstrate a solution using wireless noise-reference stations. Rather than physically connecting the reference loop to the detection electronics, the loop is connected to a preamplifier and transmitting station, which communicates to a receiving station at the main system and A/D electronics. In this first application, we use FM radio communication to broadcast and receive the noise recordings. The FM radio approach is useful, given that FM protocols and components are designed for audio frequencies (the surface NMR signal is in the band of 1-3kHz). This approach also provides for good signal synchronization since the signals remain analog until they are synchronously sampled at the main system A/D. In an alternative approach, the signals can be digitized at the remote reference station, using GPS synchronization, and broadcast digitally to the main detection electronics.

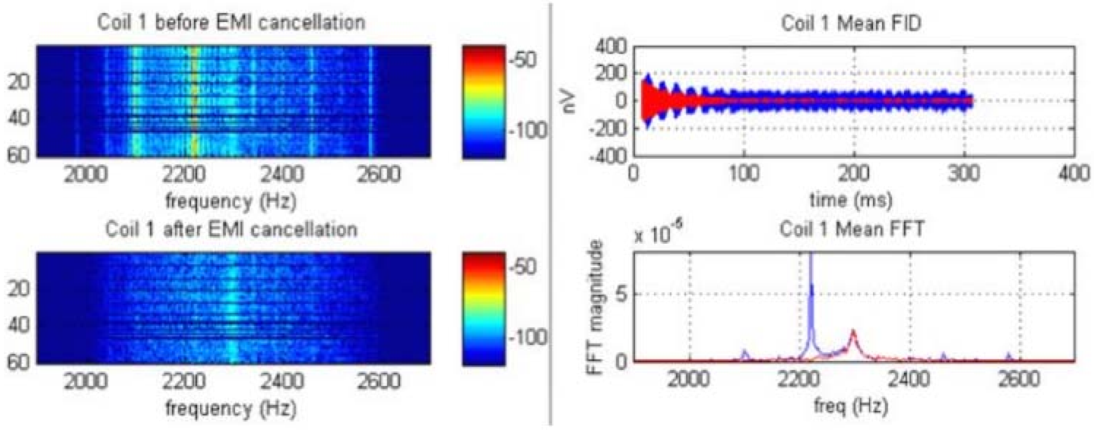

Figure 3. Field demonstration of noise cancellation using a wireless FM reference station. Left: frequency spectra for 60 records before noise cancellation (top) and after (bottom). An NMR signal is seen at ~2300Hz and we also see a number of 60Hz powerline harmonics. Right: Averaged signals for the 60 records before noise cancellation (blue) and after (red).

MOBILE COIL PLATFORMS

While wireless communication can enable noise reference coils to be left in place, the main NMR detection loop must still be physically moved to cover a survey area. If SNR is not a limiting factor, the deployment, collection, and movement of the detection coils will be the most time consuming aspect of a survey. To alleviate this barrier to survey speed, we have developed and demonstrated three mobile platforms that can be deployed in a number of different terrains. These platforms are shown in Figure 4. At left, we show a sheet array design where a 2D coil array is affixed to a flexible and durable mat that can be towed behind a vehicle. In the middle, we show a suspension ring that can support a single coil and be transported manually by a center mast. At right, we show a variant of the suspension ring that is lifted by a central helium balloon.

Figure 4. Mobile coil deployment platforms for rapid scanning surface-NMR. Left: A 2D sheet array; Middle: a suspension ring; Right: a balloon-borne suspension ring.

FIELD DEMONSTRATIONS

We have demonstrated these advancements at a number of field sites in the western United States. A series of measurements were conducted at the Department of Energy East River Catchment Site in the Rocky Mountains. The site terrain and survey geometry are shown in Figure 5. The site was surveyed using a 2D sheet array incorporating three overlapping coils, each 9 meters in diameter. A 150m transect across the catchment was acquired using stations spaced 5m apart with a measurement time of 22 minutes per station (a transect speed of 15m per hour). Data were acquired using both on-resonance pulses and adiabatic pulses.

Figure 5. The DoE East River Catchment Site. Left: site terrain and 2D sheet array. Right: survey geometry.

In Figure 6, we show a 2D inversion of the on-resonance dataset spanning the north east half of the survey. The survey, acquired at unprecedented speed, reveals connections between surface water and groundwater features, including highlighting the location of a known paleochannel. In this case, where on-resonance pulses are used, the increase in survey speed is afforded primarily by the use of the mobile coil platform.

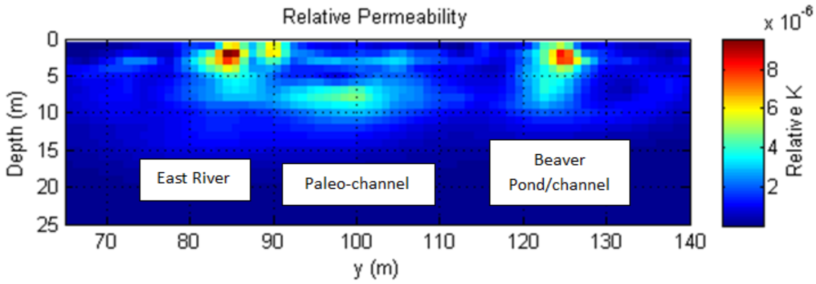

Figure 6. Inversion result for on-resonance transect at East River Catchment Site.

In Figure 7, we present results of the survey using an adiabatic excitation pulse. In this case, the data are not inverted for depth imaging but are instead simply plotted to show the mean NMR signal amplitude as a funciton of position. This mean signal amplitude is interpreted as a qualitative indicator of relative permeability. We observe here that the primary features in the on-resonance data inversion are prominantly reflected in the adiabatic transect result. The signal to noise of the adiabatic inversion result, however, was approximately four times greater than for the on-resonance dataset.

We can simulate the extent to which this high signal to noise can be leveraged for faster measurement speed by creating subsamples of the data with reduced stacking. In overlapping lines, we plot results for the full dataset consisting of 48 pulse moments, as well as reduced datasets with as few as 6 pulse moments (1/8th the data density). We find that even the most downsampled dataset still reflects the primary features along the transects and highlights the zones of most mobile water. This most downsampled result corresponds to an effective survey speed of 100m/h, opening the door to efficient and cost-effective wide area mapping.

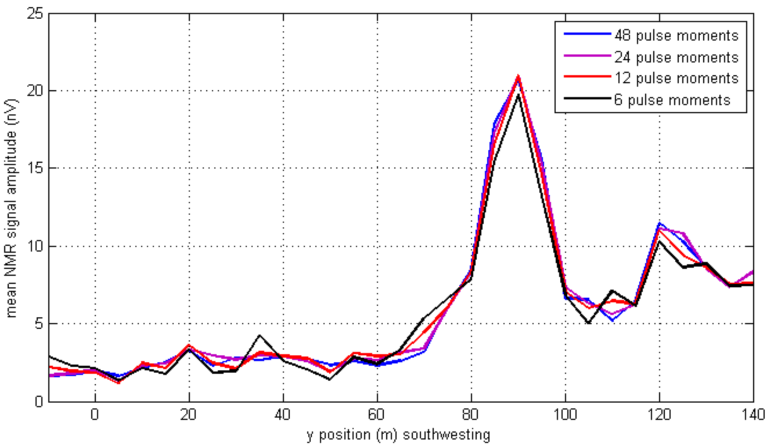

Figure 7. Mean signal amplitudes for the adiabatic survey plotted as position along the transect. Results are shown for the full dataset using 48 pulse moments (15m/hr) and for datasets downsampled to as low as 6 pulse moments (100m/hr)

CONCLUSIONS

Improvements to surface-NMR acquisition, instrumentation, and survey deployment shown here provide unprecedented enhancements in measurement efficiency. In this study, we have focused primarily on shallow groundwater mapping targets. Extending these approaches to deeper groundwater mapping will require appropriate platforms to support larger detection coils. Continued developments along this path are expected to transform surface-NMR from a stationary point measurement technique into a practical wide-area mapping method. Increased survey efficiency will ultimately reduce survey costs and will allow this powerful method to be applied across a growing range of applications.

ACKNOWLEDGMENTS

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